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OCTOBER, 1944
No. 406
Vol. XLVIII.

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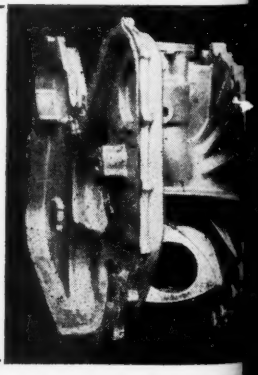

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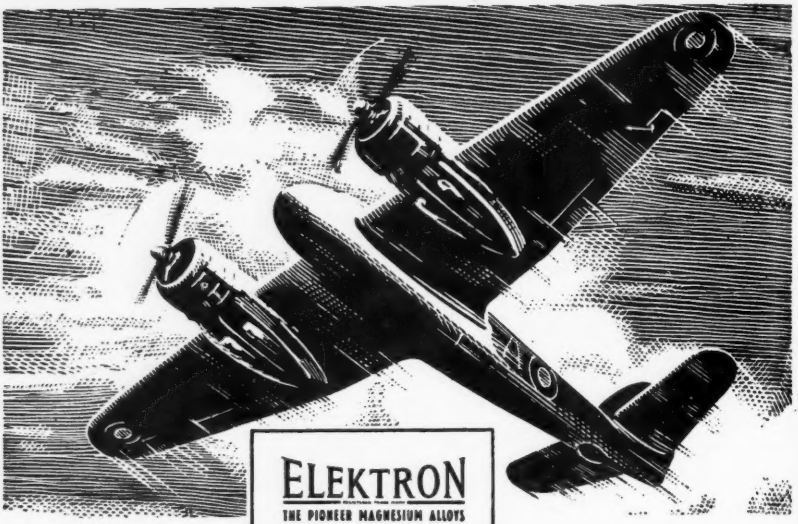

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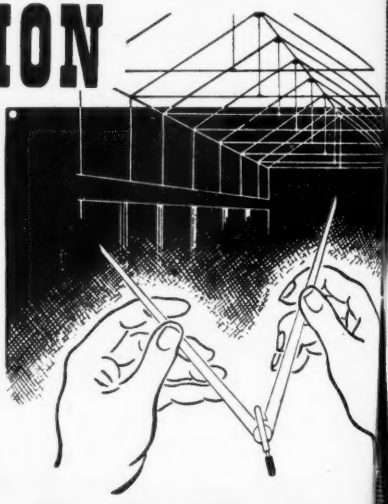

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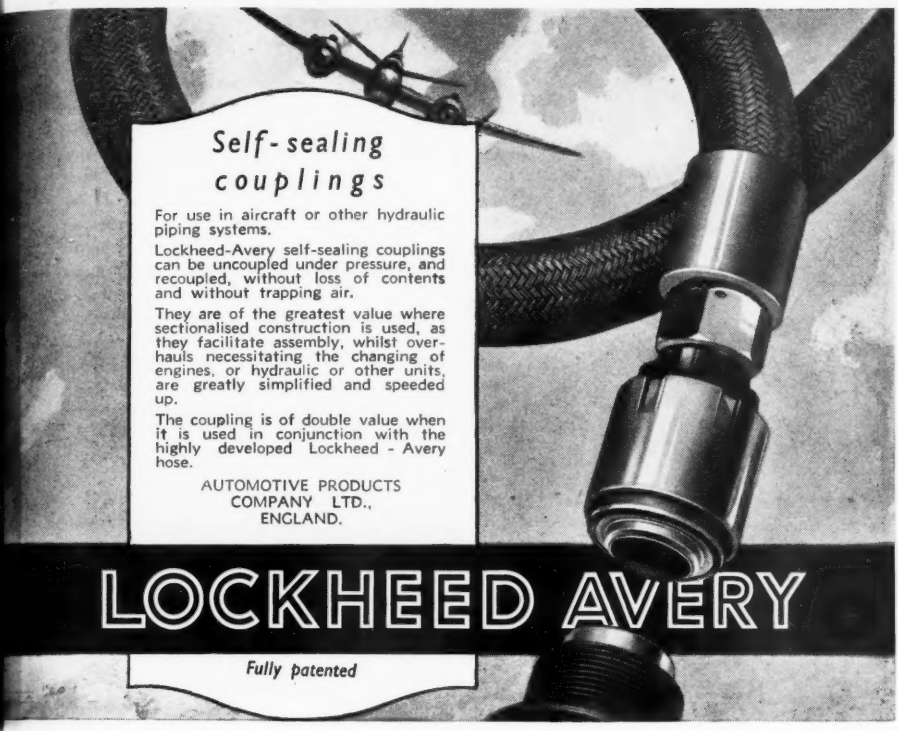

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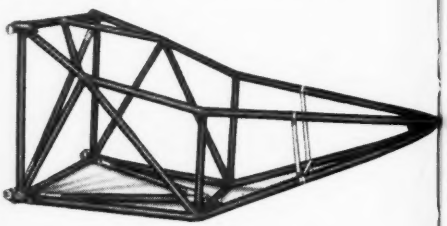

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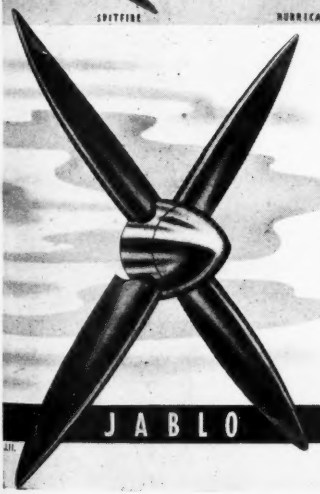

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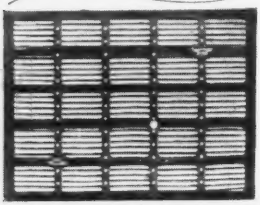

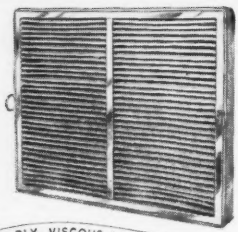

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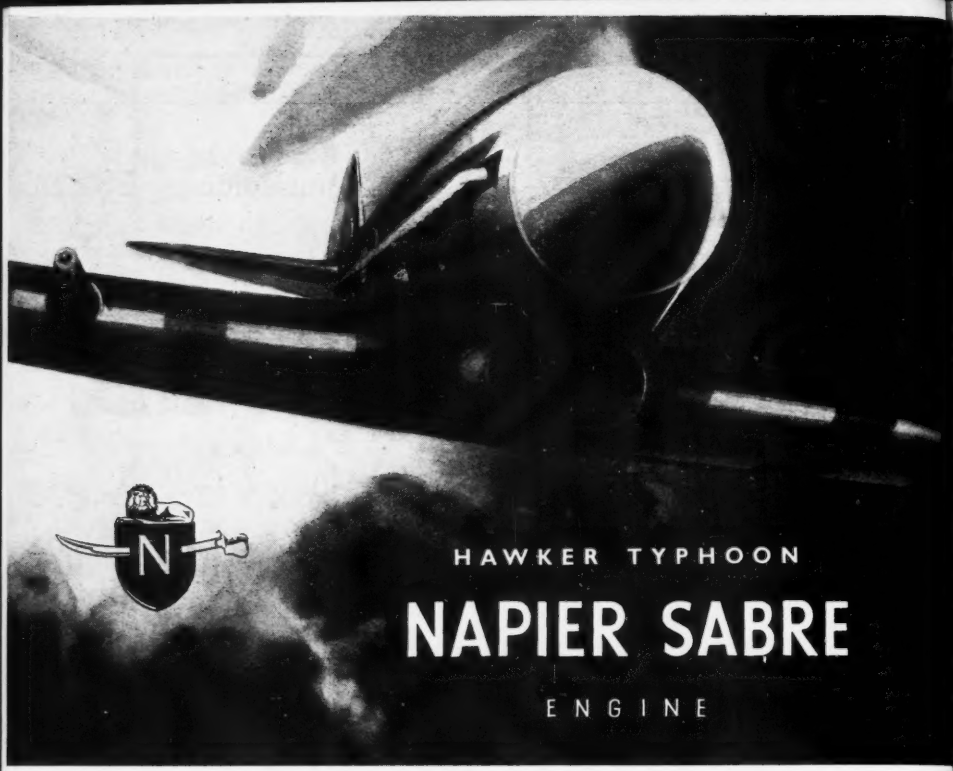

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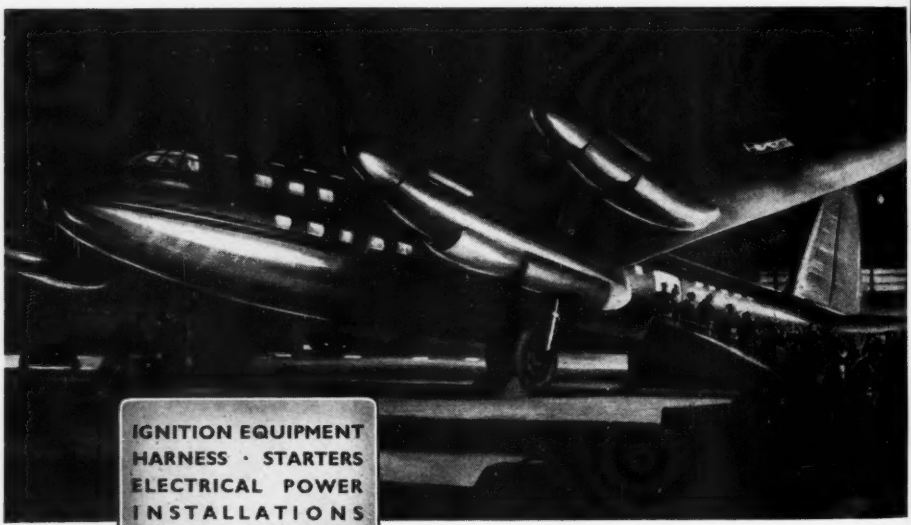

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OCTOBER, 1944.

Civil Aviation Discussion.

A discussion on Civil Aviation will be held on Saturday, November 4th, 1944, in the Lecture Hall of the Institution of Mechanical Engineers, by kind permission of the Council of the Institution.

The discussion will be an all day discussion, beginning at 10.30 a.m. and ending about 6.0 p.m. with intervals for lunch and tea. The discussion will be divided into sections dealing with economics, aircraft and aero engine design, route facilities (meteorology, radio, aerodromes, etc.), and the selection and training of personnel.

Lord Brabazon will be in the chair.

It should be noted that non-members will not be admitted without a ticket obtained through a member. Each member will be limited to one visitor's ticket.

Chair of Civil Engineering, University of Bristol.

The Council of the University of Bristol has appointed Dr. A. G. Pugsley, Fellow of the Society, to the Chair of Civil Engineering.

Dr. Pugsley is well-known for his contributions to engineering science, particularly in connection with the structural design of aircraft, airworthiness, and the aero elastic problems involved.

Zaharoff Chair of Aviation.

Professor L. Bairstow, Fellow of the Society, is retiring from the Zaharoff Chair of Aviation at the end of September, 1945, and will be succeeded by Mr. A. H. Hall, of the Royal Aircraft Establishment.

Increase in Price of the Journal.

The Council have decided that on and from January 1st, 1945, the price of the Journal should be increased to 7s. 6d. per issue to non-members (£4 10s. per annum).

32nd Wilbur Wright Memorial Lecture—Correction.

The fourth paragraph on page 349 of the September, 1944, Journal and page 15 of the Reprint should be amended to read:—

" Fig. 13 illustrates the Model D Hispano liquid-cooled 90°V 8-cylinder engine, rated at 200 h.p. Noteworthy features are the propeller reduction gear, with provision for a gun firing through the propeller shaft, cast aluminium pistons, cast aluminium cylinder blocks with closed end forged steel barrels screwed in, and cored water passages, and an interesting overhead camshaft operated valve gear.

" Another interesting French group of liquid-cooled engines was that produced by Lorraine-Dietrich. Their type 13, which was a 12-cylinder 60°V engine of 400 h.p. is shown in Fig. 14. The cylinders, etc., to rockers (as printed)."

Branch Lectures.

DERBY BRANCH.

Arrangements have been made for the following meetings of the Derby Branch to be held in the Rolls Royce Welfare Hall, Nightingale Road, Derby :—

Monday, 2nd October, 1944, at 6.30 p.m. Dr. Arthur Street, and a film " Diecasting " by the courtesy of the Imperial Smelting Corporation, Ltd.

Monday, 6th November, 1944, at 6.30 p.m. Sir Frederick Handley Page (Subject to be announced later).

Monday, 4th December, 1944, at 6.30 p.m. Annual General Meeting. Also a lecturer and film " The Ace of Blades " by courtesy of The Airscrew Company, Ltd. Mr. A. G. Elliott will be in the Chair.

LUTON BRANCH.

The following Lectures have been arranged by the Luton Branch of the Society to be held at the Technical College, Luton :—

Wednesday, 4th October, 1944, at 7.15 p.m. Presidential Address. " Our Aircraft Industry " by Captain P. D. Acland, Managing Director, Percival Aircraft, Ltd., Luton.

Wednesday, 1st November, 1944, at 7.15 p.m. " Flying Boats " by Mr. A. Gouge, B.Sc., F.R.Ae.S., of Saunders Roe, Ltd.

Wednesday, 6th December, 1944, at 7.15 p.m. " Design and Operation of Deck Landing Aircraft " by Mr. G. E. Petty, F.R.Ae.S., Chief Designer, Blackburn Aircraft Ltd.

Wednesday, 10th January, 1945, at 7.15 p.m. " Flight Testing of Aircraft Control and Stability " by Dr. D. Cameron, Ph.D., Senior Technical Officer, M. & A.E.E.

MEDWAY BRANCH.

The following Lectures have been arranged by the Medway Branch of the Society :—

Monday, 9th October, 1944, at 7.15 p.m. " Lay-out Reproduction " by Mr. R. E. Flaxman of Short Bros., Ltd.

Monday, 13th November, 1944, at 7.15 p.m. " Some Aspects of the American Aircraft Industry " by Dr. D. M. A. Leggett of the Royal Aircraft Establishment.

Monday, 11th December, 1944, at 7.15 p.m. An evening of films.

Monday, 8th January, 1945, at 7.15 p.m. " Light Alloy Castings " by Mr. F. Hoult of Kent Alloys.

Monday, 12th February, 1945, at 7.15 p.m. " Compressibility " by Dr. Hilton.

Monday, 12th March, 1945, at 7.15 p.m. " Engine Installations " by Mr. F. Mayer.

Monday, 9th April, 1945, at 7.15 p.m. " Work in an Experimental Seaplane Tank " by Mr. L. Smith of Short Bros., Ltd.

Changes in the Honorary Secretaryship of the following branches should be noted:—

Brough Branch—D. R. Adams, Esq., A.F.R.Ae.S., Blackburn Aircraft, Ltd., Brough.

Luton Branch.—S. A. Clark, Esq., A.R.Ae.S., c/o D. Napier & Son, Ltd., Luton.

Portsmouth Branch—D. H. Wilson, Esq., A.F.R.Ae.S., c/o Airspeed, Ltd., The Airport, Portsmouth, Hants.

Graduates' and Students' Section.

Important Notice.—In accordance with a decision taken at the last Annual General Meeting of the Section, the Committee wishes to arrange for each nucleus of members, whether at firms, establishments or colleges to have its views on the affairs of the Section more adequately represented.

It is hoped to send out to such nuclei a questionnaire on the affairs of the Section, and at a later date to arrange a meeting for a more adequate airing of views.

The Committee would, therefore, be grateful if members of the Section would contact their fellow members at their firm or college and from their number elect one member to correspond with the Secretary of the Section.

When a representative has been chosen, will he please write to the Secretary giving his own name and address, the name of his firm, or college, and list of the names of the members in the group.

The Honorary Secretary of the Graduates' and Students' Section would like to hear from some more members of the Section.

Secretary: E. J. ARCHBOLD,
27, North View, Eastcote,
Pinner, Middlesex.

A meeting of the Graduates' and Students' Section will be held in the Library of the Society at 4, Hamilton Place, W.1, on October 4th at 7.30 p.m., when Squadron Leader Stewart, R.A.F., will lecture on "Some Physiological Aspects of Flying."

By kind permission of the Airscrew Company a meeting of the Section will be held at the Weybridge Works of the Company on Sunday, October 29th, at 3.30 p.m. sharp. The business will be as follows:—1, Visit to the Company's fan testing wind tunnel; 2, Short talk by Mr. J. A. C. Williams, A.F.R.Ae.S., Chief Technical Assistant, on "Fan Design"; 3, Tea in the canteen; 4, Film show, including the Company's colour film "The Ace of Blades," dealing with the manufacture and repair of wooden airscrew blades.

Numbers attending are limited to 140 and those wishing to attend should send a postcard at once to the Graduates' and Students' Secretary.

Election of Members.

The following members were recently elected:—

Associate Fellows.—Albert William Brittain, Douglas John Colliver, Philip Henry Cosier, Robin Ralph Jamison, Samuel Robert Marshall Nichols.

Associates.—Frederick Windsor Ansted, Ronald Geoffrey Anderson, Frederick John Andrews, Henry Bradley, Rex Kenneth Clark, Stanley Cronshaw, Frederic James Canham, James Jump Davies, Donald Eyre, Tormod Olaf Fjaerem, William Alan Kenneth Grant (from Student), Willis Greenhalgh, John Alexander Harris, Frederick

Thomas Hopkins, Frank Edward Hunt, William Stanley Jackson, William Henry Lear, Forester Lindsley, Robert McLarren, William George Matthews, Charles Andrew Mulholland, Stephen Adams Newbigin, Reginald Herbert Pelling, Harold Priestley, James Ramsden, Neil Rowls, John Bertram Sayers, William Henry Shortland, Robert Francis Simon, William Philip Skinner, Norman Smith, Paul Torda, Raymond Curteis Warren, Joseph Sydney Wigley.

Graduates.—Clifford Ernest Cockle, Roger Quentin Eden Eden (from Student), John Smithurst Elliott, Laurence Harry Gould, Emlyn George Havard (from Student), Arthur Ingham McCutchan, Golda Sztern.

Students.—Douglas Ronald James Colpus, Gordon Hubert Conisbee, Jack Sidney Dean, Neville John Ebsworth, Roy Reginald French, Leslie James Green, Alan Hemming, Frank Hinde, Peter Gerald McNab Holmes, Peter Eustace Kerswell, Khan Iftikhar Hassan Khan, Francis John Low, Keiran Thomas McKenzie, Gordon Ross Nicoll, Harold Frank Parkin, Robert Springthorpe Sowter, Robert Welch, Joseph Keith Wharton, Robert Harvey Wright.

Companions.—Frederick Allen, Alfred John Atkinson, William Henry Brown, William James Ferguson Fenton, John William Limmer, James Collingwood Burdett Tinling, Rolf Dudley Williams.

Additions to Library.

Pamphlets in italics, with location reference following in brackets.
Books marked * and ** may not be taken out on loan.

A.d.27.—*Wind Tunnels. (Reprint from articles in "The Recorder," 11/3/44, and "Plastics," April,* 1944.) Airscrew Co., Weybridge. (Y.1.d.6.)

B.a.323.—The Book of Westland Aircraft. A. H. Lukins. (Ed. by D. A. Russell.) Aircraft (Tech.) Publications, Ltd. 1944. 12/6.

B.a.324.—*Seafire III (M.A.P. Press Release,* 7/9/44.) (Y.3.iii.30.)

B.a.325.—*Bruch und Aufbau einer G-24. Junkers A-G.* ca. 1927. (Y.33/31a.)

B.a.326.—*Entwicklung der Junkers G-38. Junkers A-G.* ca. 1930. (Y.33/43a.)

BB.b.111.—*Bericht über die Bruchprüfung eines Junkers F-13 Flugzeuges nach 8-jährigem Flugbetrieb. Junkers A-G.* ca. 1930. (Y.33/44a.)

*D.b.216.—*Second Report of an Independent Committee on the Future of Civil Aviation, May,* 1944. *(Capt. A. G. Lamplugh, Chairman.)* (PD.2.b.7.)

*D.b.217.—Report of Conference of International Air Traffic Operators, May, 1944. (Lord Grimthorpe, Chairman.)

D.b.218.—*The Future of Civil Aviation. (Cantor Lecture,* 1944.) *Sir Roy Fedden. Royal Society of Arts. (Stencil.)* (Y.6.b.29.)

D.b.219.—*Twenty-five Years of Civil Aviation Pioneering. (Article in "The Recorder," August 26th,* 1944.) (Y.6.b.30.)

D.b.220.—*Air Links of Empire. John C. Nelson. Junkers A-G.* ca. 1930. (Y.6.a.4a.)

D.c.95 and 96.—*Some Factors in the Design of Civil Land Aerodromes. Graham Dawbarn. (Reprint from "Intava World," May,* 1944.) 2 copies. (Y.6.ii.a.34 and 35.)

D.f.44.—*Report on Collision between Ju. 52 and Flamingo Sports-plane. W. Polte. Junkers A-G.* 1932. (Y.12.a.4a.)

E.f.104.—Flight Mechanic's Handbook. G. W. Williamson. George Newnes, Ltd. 1944. 12/6.

E.f.105.—*Notes on the Storage of Aircraft. P. V. Hoare.* (*From R.Ae.S. Journal, June and July,* 1922.) (Y.8.c.8.)

G.a.69.—*Sheet Metal Pattern Development. W. Cookson.* (*Article in "Engineering," July 14th,* 1944.) (Y.13.a.17.)

G.e.J.24.—*Light Alloys in Post-War Britain.* (*Reprint of lecture before Royal Society of Arts,* 2/2/44.) *E. C. Goldsworthy. High Duty Alloys,* 1944. (PG.4.b.8.)

G.e.J.25.—*Shipbuilding and Light Alloys.* (*Reprint from Transactions of Inst. of Engineers and Shipbuilders in Scotland,* 1943.) *E. C. Goldsworthy. High Duty Alloys,* 1944. (PG.4.b.9.)

L.b.41.—Aviation Questions and Answers. C. D. Duguid and W. H. McMahon. Sir Isaac Pitman, 1944. 3/6.

L.k.43.—*Fran en tur i Norrbotten med Röda Korsets Ambulansplan. Fritz Bauer.* (*Reprint from Svenska Röda Korsets Tidskrift. Heft* 8, 1928.) *Junkers A-G.* (Y.12.b.1b.)

*R.b.253.—*Air Locomotion, Dispensing with Gas and Ballast. A. Crestadoro. Longmans Green & Co.* 1868. (PR.1/1a.)

**R.c.279.—*A Method of Aerial Navigation. Patrick Weir.* (*Handwritten MS. with pencil drawings.*) 1908. (Special Drawer.)

R.f.97.—*Britain's Royal Aero Club. Frank Stuart.* (*Article in "Everybody's,"* 6/9/44.) (Y.11.iv.a.28.)

S.d.89.—Keep the Peace through Air Power. Alan Michie. Henry Holt, New York. 1944. (Galley proofs, in file case.)

S.d.90.—*World Authority. Capt. R. E. G. Fulljames.* (*Stencil.*) 1944. (Y.17.c.W.)

*UC.8.—*Australian Council for Aeronautics: Reports.* (1944.) *Introduction*: The Inauguration of the A.C.A. Bruce Foster.

ACA-1: Interference in a Wind Tunnel of Octagonal Section. G. K. Bachelor.

ACA-2: Interference in a Wind Tunnel of Regular Octagonal Section. Betty L. Gent.

*UU.c.—*National Advisory Committee for Aeronautics, U.S.A. Technical Memoranda. No.* 1063—Gas Jets. S. Chaplygin. (From Scientific Memoirs, Moscow University, 1902.)

*WB.17/16.—The Nickel Bulletin, Vol. 16, 1943. Mond Nickel Co. 1944.

*Y.9.B.—*Science Library Bibliographies* (1944). No. 602—Dissipation of Natural Fog. No. 603 Cloud Formation and Dispersal by Aeroplanes. No. 604—Vapour-lock in Fuel Systems.

**Baden-Powell Miscellania.* (Manuscripts, articles, etc., by the late Major B. F. S. Baden-Powell, collected in box file Y.21.i.)

Aeronautics. (MS. article, for Blackie's "Popular Cyclopædia," 1898.)

Ballooning and Aeronautics. (Preliminary advertisement of magazine, later known as "Aeronautics.") 1908.

Q.d.58.—Club Communities: A Problem in Social Economy. Holmesdale Press. 1924.

BB.c.89.—Experiments with Aerial Screw Propellers. (Proofs of article in R.Ae.S. Journal, April, 1904.)

The Flying Chute. (Typescript, incomplete and undated.)

C.c.63.—How I Learned Ballooning. (Article in "Temple Bar," March, 1887.)

C.b.28.—International Kite Competition, 1903. (Booklet of Rules.)

Lecture on Kites. (MS. for Royal United Services Inst., 1895.)

**Baden-Powell Miscellania*—(continued).

London Alighting Ground. (Typescript, incomplete and undated.)
A New Method of Inflating Balloons. (Typescript, undated.)
The Problem of Aerial Navigation. (Typescript, undated.)
Recent Advances in Aerial Navigation. (MS. and typescript of article for "National Review," undated.)
R.c.277.—A Trip with Wilbur Wright. (Proofs of article in "Aeronautics," December, 1908.)
R.b.252.—Recent Aeronautical Progress. (Proofs of Presidential Address to Aeronautical Society, published in Journal, January, 1903.)
C.b.29.—War Kites. (Article in Pearson's Magazine, 1898.)
Some Notes on W. Wright's Aeroplane. (Typescript, 1908.)
R.c.278.—Flying Explained. (MS. of unpublished book, intended for Boy Scouts. 1910.)

J. LAURENCE PRITCHARD, *Secretary and Editor.*

THIRTY-SECOND WILBUR WRIGHT MEMORIAL LECTURE

By

SIR A. H. ROY FEDDEN, M.B.E., D.Sc.,

F.R.Ae.S., M.I.Mech.E., M.I.A.E., F.R.S.A., M.S.A.E., M.I.Ae.S.

(*Continued from p.* 389).

SECTION 7.—POST-WAR RECIPROCATING ENGINES AND POWER PLANT.

Earlier sections have dealt with engines which have been developed almost entirely with the object of war and destruction. The fighter engine has been pushed all the time harder and harder to obtain greater output, with increased rate of supercharge, higher critical altitude, and more power to manœuvre under all possible conditions and attitudes of the aircraft. Performance has been achieved at almost any expense, provided reliability was ensured for a given period; such items as the time between overhaul and fuel consumption have been secondary considerations. In a similar way bomber engines have been continually stepped up in power to give maximum output at rich mixture for take-off, so as to project the greatest possible load of bombs into the air, and every attention has also been given to providing the highest weak mixture cruising power at altitude, in order to allow for the necessary power to maintain flight at a reasonable altitude during the early part of the mission, when the machine is fully loaded.

There has been continuous and earnest development of these engines to meet new military conditions, such as, for example, the need for devices to obscure the flame and glow from the engines at night, but comparatively little attention has been given to cost, either in regard to materials, life or maintenance, and all the time the single goal which has been before the aero engine industry has been the all important one of performance.

When the war is won, we shall obviously continue to provide power plant for our military air force for policing purposes and also for our civil aircraft, and we shall employ those engines that are available at the time, but we have learned so much during the present war that there are considerable strides that can be made for the future.

In principle, I am averse to employing military engines for peace-time use, although obviously we shall not throw away all the remarkable experience that we have gained in the war. As our 12 and 14-cylinder engines have proved to be classic types when pushed to the ultimate, for war-time purposes, we shall retain all their good features; at the same time, it is believed that de-rated military engines are unlikely to be entirely suitable for civil operation. If we take almost any of the successful types of aero engines, which have been used during the war and de-rate them, with one or two exceptions they do not fit in with the programme of civil aircraft required and the use of these engines should be looked upon as a temporary measure for the immediate post-war period, while existing types and sizes are amended and re-designed for civil work.

It is considered essential, however, to develop new military engines, because we must keep our military aircraft right up to date, and maintain technical superiority, even if the machines are built only in comparatively small quantities. It is only by doing this that we can ensure that we are not caught out again, and an intensive development programme is visualised on various new types of reciprocating engines, in which the highest technique and performance is the

one and only object, combined with reasonable life, but not complete durability in the civil sense of the word.

On the other hand, we have to develop a new family of engines for civil work, and we must approach this object with a different outlook. These engines must be light, reliable and have a long life between overhauls. In their design attention must be given to accessibility and cheap overhaul, although it is not essential to provide for any major servicing to be done with the engine in the airframe.

In order to ensure regularity of operation of civil airlines and to cut maintenance costs to a minimum, it is thought to be highly desirable that the engines should require the very minimum of servicing. Apart from the cleaning of air filters and changing of sparking plugs, it should be possible to obviate all the routine work which now has to be carried out at too frequent intervals. When any more major maintenance work or replacement is required, it should become the established procedure to change the complete power plant, and this operation should not take more than an hour, inclusive of everything.

One of the first big questions to settle in discussing prospective high power aero engines is the breathing mechanism, and I am of the opinion that the Burt McCollum sleeve will be predominant in future large aero engines in Britain. Undoubtedly, there are other interesting valve mechanisms in experimental form, but it is doubtful whether it is worth while going on with these, since it is an eight to ten years job to bring any such mechanism to an absolute standard of reliability for series production in a modern aero engine.

Although a definite recommendation has been made about the best type of valve mechanism, it would be difficult to be so categorical about the pros and cons of air and liquid-cooling for future high power air transport power plants. Before the war, air-cooling was predominant all over the world in civil aircraft. This was undoubtedly due to the fact that early civil air liners employed the old type of liquid-cooled engine with separate cylinders, individual, thin water jackets, and a multiplicity of water joints, and these, in conjunction with somewhat crude radiator systems, proved unreliable. Further, liquid-cooled engines were found to be considerably more complex and difficult to service and dismantle, and presented an entirely different proposition from the modern properly conceived liquid-cooled, self-contained power plant. This development, in combination with the latest internal modification to the engine itself, including monobloc cylinders and wet liners, and the success of this type of engine on heavy bombers in this war, may well alter the picture, and it will be interesting to see how this will work out on large air liners. The liquid-cooled engine should be slightly better on fuel consumption, and if the problems of the balance of aircraft with buried engines and pusher airscrews can be overcome, then it may well have certain advantages in conventional civil aircraft of this type, and even more so in tailless aircraft, provided due regard is given to absolute reliability and accessibility.

In view of the fact that there are likely to be big developments in the future, which may supersede the reciprocating engine in due course, it would appear that there is insufficient time left to make it worth while undertaking any major original basic work in the design of reciprocating engines, and builders of large engines should make hay while the sun shines. Assuming that the state of the war will allow us to devote some energy to the problem within the next twelve months, and accepting that any large aero engine takes at least five or six years to develop and bring into satisfactory series production, the new types of engine which I have in mind should be coming into general use by about 1950, and would have a useful life of five to ten years, during which period we are likely to see a gradual decline of the piston engine in favour of the gas turbine. It therefore behoves us to plan our new development of reciprocating engines for a reasonably short term policy, on the basis of existing types of cylinder assembly

and existing known and established geometric arrangements. Fig. 56 shows the progressive development of average engine powers and specific weight over the last forty years. The curves have been extrapolated on what seems to be a reasonable basis, and indicate that by 1960 we may expect to see engines of 8,000 h.p. with a slightly higher specific weight than prevails to-day for military engines, while the power-weight ratio shows a slight upward trend.

Bearing in mind that the smallest number of cylinders which provides satisfactory balance, in conjunction with correct firing order and smooth running, always makes the lightest engine, and the most generally acceptable one for normal use, it is submitted that the most promising procedure should be to take a developed form of a proven type of cylinder, probably of somewhat increased bore, and design this round a crankshaft or crankshafts in a geometric form which has already been proved to be satisfactory.

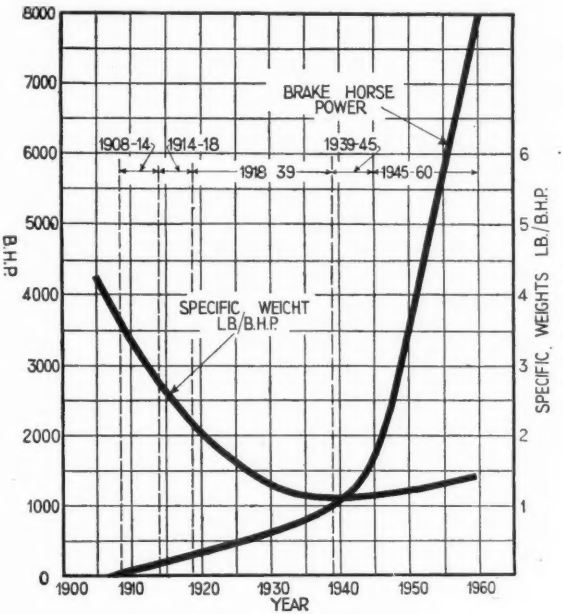


FIG. 56.

Curves of average powers and specific weights of aero engines, 1905-1960.

In the following notes an attempt has been made to review the various layouts concerned, as a guide to the future potentialities of the reciprocating engine.

Cylinder Size.

The latest liquid-cooled engine to come into production is the Rolls-Royce Griffon, and it is interesting to note that the increase in power of this engine over the Merlin has been achieved by retaining the same number of cylinders and layout, and increasing the cylinder size. This engine is giving 1,750 h.p. to-day, but I am of the opinion that we can expect it to produce over 2,000 h.p. before long, almost 170 h.p. per cylinder. This power output per cylinder is appreciably in excess of that achieved by the 5⅜in. bore Bristol or Pratt and Whitney cylinders, or the 6⅛in. bore Wright cylinders at the present time.

There is every indication that the potentialities of the sleeve valve have not yet been pursued to anything like their logical conclusion, and there is no reason whatever to doubt that sleeve valves can operate satisfactorily with larger cylinders. Bores of 6½in. for air-cooled cylinders and 7½in. for liquid-cooled cylinders should, in fact, be quite possible, giving outputs in excess of 200 h.p. for the liquid-cooled cylinder.

About the same output per cylinder is also likely to be achieved with smaller cylinders on high octane fuel, but it seems unlikely that much over this figure will be realised, except perhaps for military ratings. Fig. 57, showing the progress of boost response of the Bristol sleeve valve cylinder, gives some indication of the performances that can be expected for high duty military engines.

Geometric Layout.

If we base our predictions on a maximum of about 200 h.p. per cylinder, it then remains to examine the crankshaft layouts which are possible, and this will allow us to assess the potential power output of the various practicable types of engine.

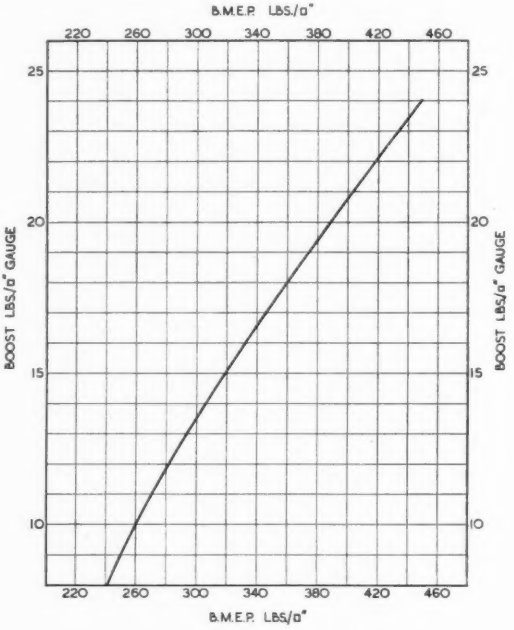


FIG. 57.

Boost response curve of Bristol Hercules sleeve valve single-cylinder.

(*a*) *V*.12.

It seems likely that the Rolls-Royce Griffon represents about the peak size for a 12-cylinder engine, but appreciable advances in power output can be expected by further development in conjunction with the use of high octane fuel. I am of the opinion that 200 h.p. per cylinder can be expected within the next few years, giving a power output of 2,400 h.p. for this type of engine. The layout is shown diagrammatically in Fig. 58.

(*b*) *V*.16.

For certain installations there would be advantages in maintaining the small frontal area of the "V" type engines, but increasing the power output by having 16 cylinders instead of 12. It would be an extremely difficult task to develop a normal crankshaft system for a high output engine of this type, but it has been shown that this difficulty can be overcome by taking the propeller shaft drive from the centre of the engine. It is doubtful, however, if this layout of engine, which is shown in Fig. 59, will become a classic type.

(*c*) *X*.24.

This layout of engine, depicted diagrammatically in Fig. 60, has been constructed in prototype form in many countries during the last 25 years. The

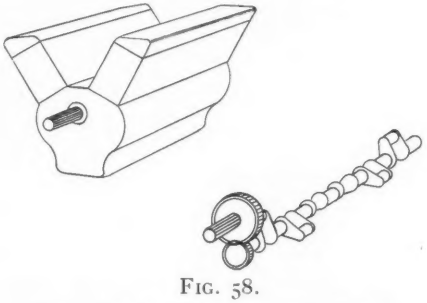


FIG. 58.
V.12 *Engine Diagrammatic Layout.*

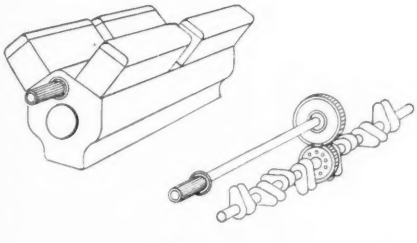


FIG. 59.
V.16 *Engine Diagrammatic Layout.*

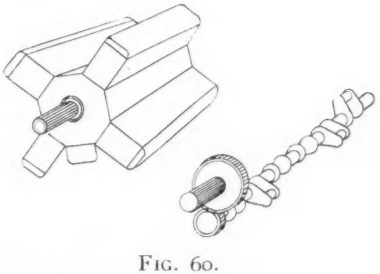


FIG. 60.
X.24 *Engine Diagrammatic Layout, Single Crankshaft.*

latest example is the Rolls-Royce Vulture of about 2,000 h.p. Many engineers, however, believe that the difficulties of coupling the 24 connecting rods to a single crankshaft outweigh the apparent advantages of a reduction in weight, and it may well be that a twin crankshaft arrangement would be more satisfactory for advanced engines of this layout. It is believed that in round terms it is not economical to transmit much over 3,000-4,000 h.p. through a single crankshaft, and that it may be more satisfactory to use two or more crankshafts for higher powers. This layout, however, is a quite possible solution for in-line, air and liquid-cooled types up to 3,000-3,500 h.p.

(*d*) *X*.24 *Twin Crank.*

In order to overcome these difficulties proposals have been made for a twin crank "X" engine, as indicated in Fig. 61. By building two "V" engines into a common crankcase it would be possible to achieve an engine with little more frontal area than a single crank "X" engine, and it seems likely that such an

engine might be constructed with less development difficulties. It would appear, however, that this type of engine has no advantage over the H twin crank layout for liquid-cooling, although it might have some advantages for air-cooling.

(*e*) *W.24 Twin Crank.*

Another line of attack for the same problem, and one which has already been worked on in America, is to build two existing V.12's into a common crankcase with geared crankshafts. The layout is shown in Fig. 62. This is undoubtedly a logical development as an emergency, as many of the existing parts of the 12-cylinder engine can be utilised, excepting, of course, the crankcase. Although this may not be the most compact way of achieving the desired power, the advantages of quick development make it worth consideration. If such a plan were followed, using a double Rolls-Royce Griffon engine for instance, it should be possible to develop a 4,000 h.p. engine for heavy machines in a comparatively

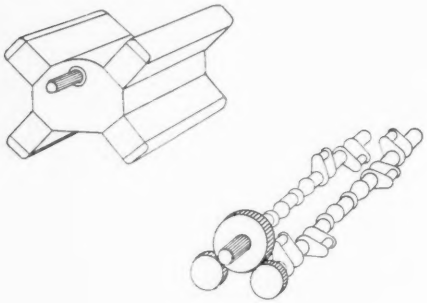


FIG. 61.

X.24 Engine Diagrammatic Layout, Twin Crankshaft.

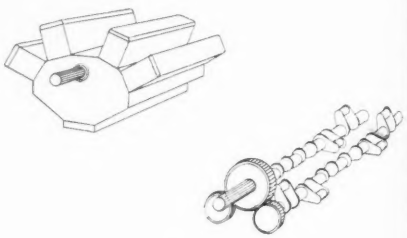


FIG. 62.

W.24 Engine Diagrammatic Layout, Twin Crankshaft.

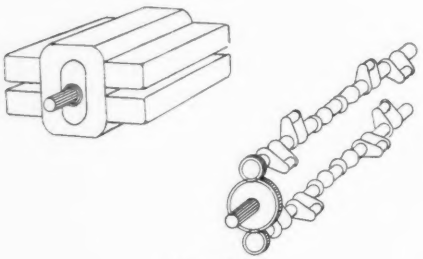


FIG. 63.

H.24 Engine Diagrammatic Layout, Twin Crankshaft.

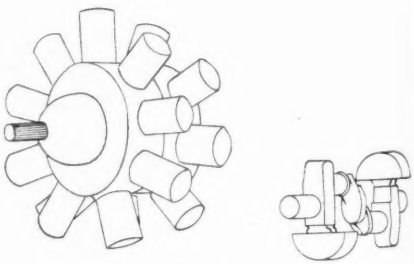


FIG. 64.

2 Bank Radial Engine Diagrammatic Layout.

short time, but it is believed that this could only be considered as a war-time policy, as the H.24 twin engine makes a more compact and better solution.

(*f*) *H.24 Twin Crank.*

The Napier Sabre of 2,200 h.p. has already proved that the "H" engine is a classic liquid-cooled type, and it is suggested that we can look forward to further engines of this layout, shown in Fig. 63, with ultimate power outputs up to 6,000 h.p. It would also be possible to use "H" type engines of 28 and 32 cylinders, but the crankshaft problems of the 32-cylinder edition would be con-

siderable, although the 28, it is submitted, is worthy of consideration, if the power demanded should exceed existing cylinder possibilities.

(g) Two-Row Radial.

The two-row air-cooled radial, shown diagrammatically in Fig. 64, has been proved both in this country and in America as a classic type, and is being built at the present time in larger numbers than any other form of engine.

At the present moment the fourteen-cylinder type is in the largest production, with power outputs of around 1,700 h.p., but the 18-cylinder radial is rapidly coming into use, with outputs of over 2,000 h.p. In the course of the next few years it is confidently believed that this type will be developed to give outputs exceeding 3,000 h.p.

(h) Four-Row Radial.

The logical successor to the 18-cylinder two-row radial is the 28-cylinder four-row air-cooled radial, and it should be possible to develop this eventually into a 4,000-5,000 h.p. engine. The valve operating mechanism, however, calls for considerable ingenuity and good design, and the satisfactory disposal of the exhaust system is a momentous task, which must be tackled from the first pencil to paper, while the overhung mounting of this size requires very careful consideration. A possible layout is shown in Fig. 65.

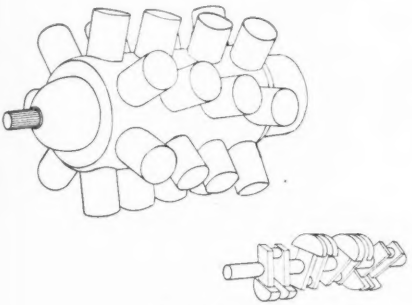


FIG. 65.

4 *Bank Radial Engine Diagrammatic Layout.*

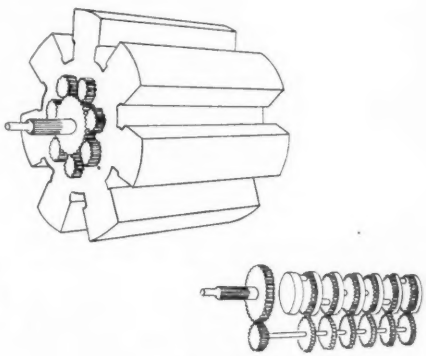


FIG. 66.

6 *Bank Radial Engine Diagrammatic Layout, Multi-Crank.*

(i) Six-Row Radial.

If we attempt to establish the largest practicable engine which can be achieved by a combination of known cylinders and known geometric layout, we come to the six-row liquid-cooled radial with seven cylinders per row, giving a total of 42 cylinders. It has already been shown that this layout, shown diagrammatically in Fig. 66, can be made to operate with small cylinders at reasonable power outputs, and it could doubtless be built with larger cylinders with a better power weight ratio and less cramping on piping, accessories, etc. Such an engine, using seven Griffon cylinder blocks, could probably be made to develop over 8,000 h.p., but the mechanical problems and the considerable difficulties in designing a neat layout of the induction and exhaust systems might mitigate against rapid development. It is my opinion that about 8,000 h.p. in one unit is the limit of size of the accepted reciprocating engine for aircraft, and that gas turbines will be preferable above this size.

It is suggested that all the foregoing engine layouts are worthy of attention, but each manufacturer is bound to have his own ideas, and one or more of these layouts will probably fit in with his school of thought.

It is believed, moreover, that there are certain sizes of new engine which are urgently required to fit particular British needs during the next five years, and the following list is an attempt to enumerate these. These engines fall broadly into three main groups as follows:—

(*A*) *Highest possible performance orthodox fighter and medium bomber.*—I am of the opinion that an engine of about 4,000-4,500 h.p. at 25,000 ft. should be developed specifically for single-seater fighters—the main requirements being compactness and light weight. Such an engine could also well be employed on a very high performance bomber. It is believed that a liquid-cooled sleeve valve "H" type engine—a successor to the " Sabre " is best fitted to fill this need.

(*B*) *Large civil aircraft and long range heavy bombers.*—For this duty, it is believed that piston engines of adequate size are required, running at comparatively light duty, with moderate boost and piston speed. Good accessibility and easy maintenance are also important features.

In view of the advent of the gas turbine, I feel that it may not be worth considering engines of much over 6,000 h.p. for the largest size at this stage. The difficulties of developing very high power reciprocating engines will be considerable, whereas the gas turbine does not suffer to nearly the same degree from the scale effect. If we base our thoughts on a 6,000 h.p. engine, this will allow four-engined machines of something like 200,000/250,000 lbs., and six-engined machines of nearly 350,000/400,000 lb.

It is believed that a 6,000 h.p. engine could best be built by retaining the " H " type liquid-cooled sleeve valve layout, with larger cylinders in 24 or 28-cylinder forms. In this same class there should also be scope for a four-bank 28-cylinder air-cooled radial, but it is doubtful if we shall see 5,000 h.p. exceeded with an air-cooled engine in the next ten years. It would, of course, be possible to gear any two of these large units together, thus having eight engines operating on four airscrew centres, but 10,000 h.p. would be the absolute upper limit from a propeller point of view, as far as we know at present.

The next most urgent engine is probably one to give 3,000 h.p for take-off and a 50/60 per cent. continuous cruising power at 25,000-30,000 feet. It is unlikely that any existing military engine can be made to fulfil this purpose adequately, and a re-designed engine is required. Either a liquid-cooled "H" 24-cylinder or an air-cooled 18-cylinder radial could fulfil this purpose.

Coming to the next smaller size, an engine is required for medium sized transport machines to give some 1,800 h.p. for take-off and a 50/60 per cent. continuous cruising power at 25,000-30,000 feet. In my opinion, a civil form of the Rolls-Royce Griffon would fill the bill as the liquid-cooled version, while a 14-cylinder sleeve valve of about 42 litres would be an attractive air-cooled version.

The last engine in this range is probably one of about 1,300 h.p. for medium sized general purpose transports. Here a suitable civil version of the Merlin might well fill the bill, although a thoroughly up to date nine-cylinder single-row radial would probably be the most straightforward and economical type.

(*C*) *Feeder line aircraft and trainers.*—The largest engine required in this category is believed to be about 800-850 h.p. and although we are dealing with feeder line machines, it is believed that a really high class thoroughly developed engine is wanted. A revised version of the Rolls-Royce Peregrine or the Bristol Aquila should meet this bill adequately.

The smaller engines in this category, from 600 h.p. down to 100 h.p., would probably all fill their functions best with air-cooling, and the de Havilland and Armstrong Siddeley companies have for some considerable time produced certain types, falling within this range, which have built up enviable reputations all the world over for reliability and good service. There is, however, still an opening for modern refined design to cater for some of these lesser categories, and V.12-6 and four in-line, and nine, seven and five-cylinder radial layouts provide con-

siderable scope for choice of types. Fig. 67 shows the latest Gipsy Queen IV supercharged type, rated at 295 b.h.p. at sea level.

Exhaust Heat.

As the power of reciprocating engines increases so will the difficulties of exhaust manifolding increase, and disposal of the exhaust heat is likely to prove a major problem in the larger engines which we have been considering. Apart from the difficulties of manifolding, the amount of energy which is being dissipated is so large that it must be carefully conserved in some suitable way.

The Two-Stroke Petrol Engine.

Although the foregoing remarks have all been confined to the four-stroke engine, this does not mean to suggest that the two-stroke cannot be made a success.

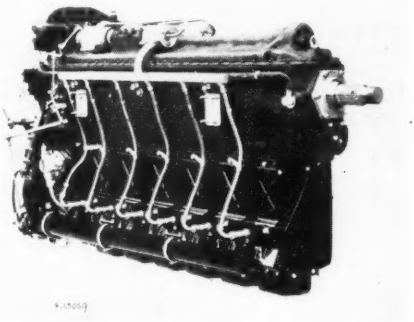


FIG. 67.

De Havilland Gipsy Queen 295 h.p. air-cooled inverted 6-cyl. in-line supercharged, 1943.

Now that the sleeve valve is an accomplished fact, there would appear to be no outstanding difficulties in the way of a petrol injection two-stroke. It is suggested that the advantages of the two-stroke engine are best suited for making the most compact high power engine for fighters. Assuming that the potential power output of the two-stroke is limited by the intensity of heat flow, it should still be possible to develop at least 50 per cent. more power for a given size of engine than with a four-stroke. On the other hand, there are considerable difficulties in achieving good fuel consumption, in view of the very high blower power required, and the mechanical development might take some time to overcome. As jet propulsion seems to be ideal for this type of machine, therefore, it is considered that it would be more advisable to concentrate on the gas turbine.

Engine and Power Plant Weight.

In recent years the advantages accruing from the utilisation of improved fuels, and the metallurgical and technical skill on the general refinement and lightening of engines, have become progressively more obscured by the influence of the supercharger, and any comparison of specific weights based on the take-off or ground level power cannot be used as a criterion of excellence. For example, if we consider two marks of a given single speed supercharger type of engine, the one with a rated altitude of, say, 15,000 ft. and the other 10,000 ft., the weight will be the same for both, but the power available at sea level will differ

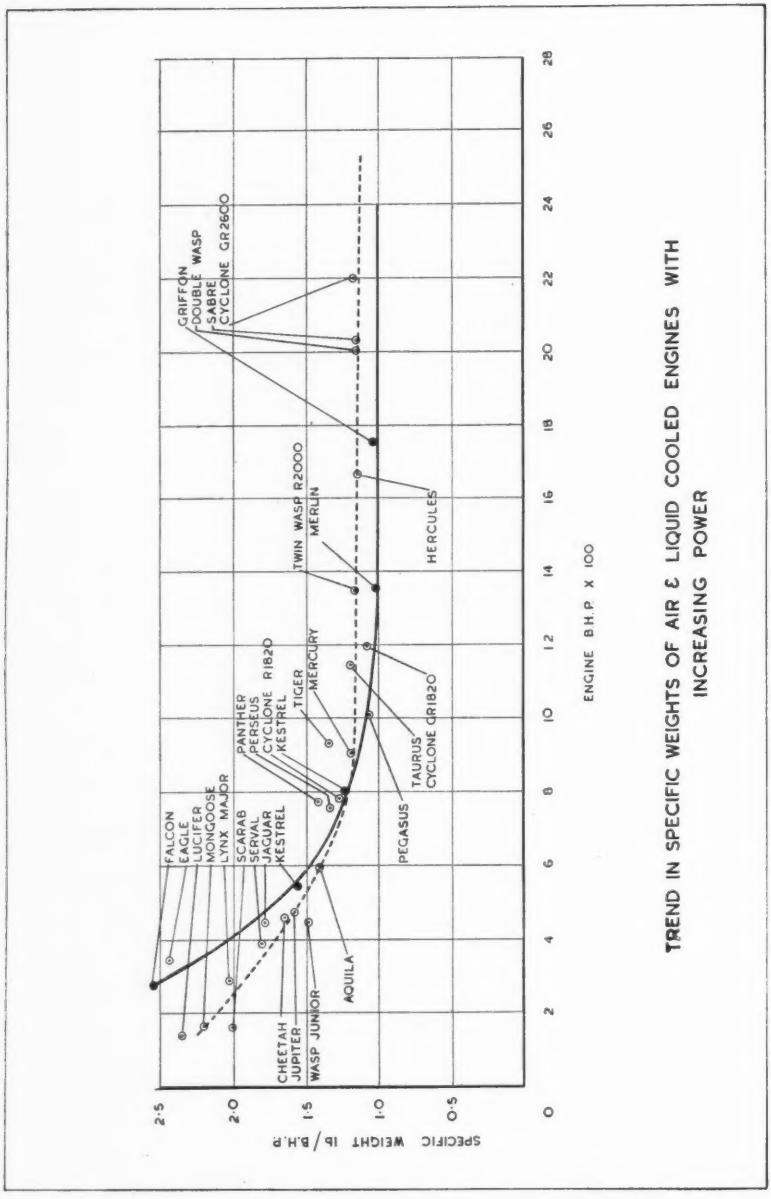


FIG. 68.

Curve showing trend in specific weights in air- and liquid-cooled engines.

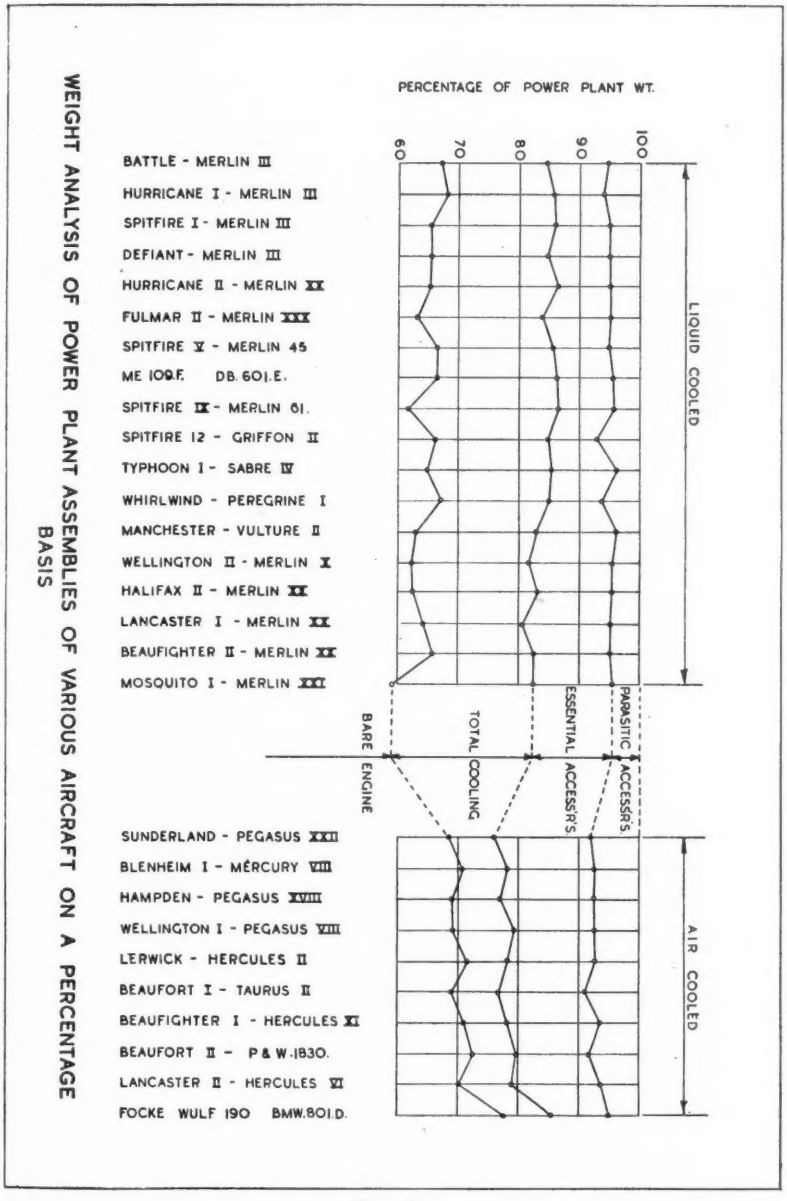

WEIGHT ANALYSIS OF POWER PLANT ASSEMBLIES OF VARIOUS AIRCRAFT ON A PERCENTAGE BASIS
PERCENTAGE OF POWER PLANT WT.
60
70
80
90
100
BATTLE - MERLIN III
HURRICANE I - MERLIN III
SPITFIRE I - MERLIN III
DEFIANT - MERLIN III
HURRICANE II - MERLIN XX
FULMAR II - MERLIN XXX
SPITFIRE V - MERLIN 45
ME 109F. DB. 601.E.
SPITFIRE IX - MERLIN 61.
SPITFIRE 12 - GRIFFON II
TYPHOON I - SABRE IV
WHIRLWIND - PEREGRINE I
MANCHESTER - VULTURE II
WELLINGTON II - MERLIN X
HALIFAX II - MERLIN XX
LANCASTER I - MERLIN XX
BEAUFIGHTER II - MERLIN XX
MOSQUITO I - MERLIN XXI
LIQUID COOLED
BARE ENGINE
TOTAL COOLING
ESSENTIAL ACCESS'R'S
PARASITIC ACCESS'R'S
SUNDERLAND - PEGASUS XXII
BLENHEIM I - MERCURY VIII
HAMPDEN - PEGASUS XVIII
WELLINGTON I - PEGASUS VIII
LERWICK - HERCULES II
BEAUFORT I - TAURUS II
BEAUFIGHTER I - HERCULES XI
BEAUFORT II - P & W.1830.
LANCASTER II - HERCULES VI
FOCKE WULF 190 BMW.801.D.
AIR COOLED

FIG. 69.

Graph of percentage weight of power plant assemblies.

Curve showing trend in specific weights in air- and liquid-cooled engines.

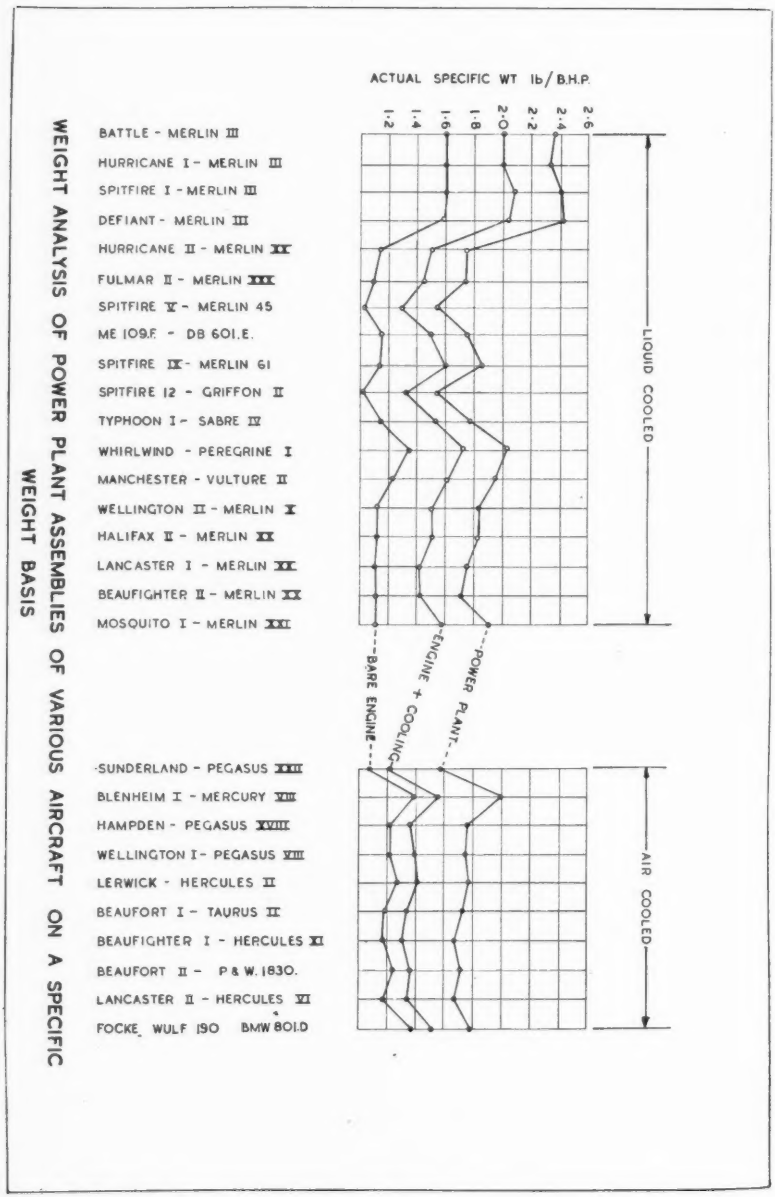

WEIGHT ANALYSIS OF POWER PLANT ASSEMBLIES OF VARIOUS AIRCRAFT ON A SPECIFIC WEIGHT BASIS
ACTUAL SPECIFIC WT lb/B.H.P.
1·2
1·4
1·6
1·8
2·0
2·2
2·4
2·6
BATTLE - MERLIN III
HURRICANE I - MERLIN III
SPITFIRE I - MERLIN III
DEFIANT - MERLIN III
HURRICANE II - MERLIN XX
FULMAR II - MERLIN XXX
SPITFIRE V - MERLIN 45
ME 109.F - DB 601.E.
SPITFIRE IX - MERLIN 61
SPITFIRE 12 - GRIFFON II
TYPHOON I - SABRE IV
WHIRLWIND - PEREGRINE I
MANCHESTER - VULTURE II
WELLINGTON II - MERLIN X
HALIFAX II - MERLIN XX
LANCASTER I - MERLIN XX
BEAUFIGHTER II - MERLIN XX
MOSQUITO I - MERLIN XXI
LIQUID COOLED
BARE ENGINE
ENGINE + COOLING
POWER PLANT
SUNDERLAND - PEGASUS XXII
BLENHEIM I - MERCURY VIII
HAMPDEN - PEGASUS XVIII
WELLINGTON I - PEGASUS VIII
LERWICK - HERCULES II
BEAUFORT I - TAURUS II
BEAUFIGHTER I - HERCULES XI
BEAUFORT II - P & W. 1830.
LANCASTER II - HERCULES VI
FOCKE WULF 190 BMW 801.D
AIR COOLED

FIG. 70.

Graph of specific weight of power plant assemblies.

considerably. Consequently, the specific weight, based on take-off powers, will cause the engine with the highest rated altitude to show up badly against the other.

It is difficult to make a general rule for the rate of increase of specific weight with increased altitude rating, but an examination of a number of examples indicates that this is of the order of 10 per cent. to 15 per cent. per 10,000 ft. It is useful, however, to examine data on existing engines, and power plants, and Fig. 68 shows the trend in specific weights of different British and American models which can be taken as representative of good practice on air and liquid-cooled motors. It is interesting to note that, for types over 1,000 h.p. there has been little reduction in the specific weight. • It is also instructive to study Figs. 69 and 70, which by means of graphs show the percentage weight and the specific weight for the various elements of the power plant; for example, bare engine, cooling system, etc. It will be seen from these graphs that the weight advantage which the liquid-cooled in-line engine has gained in the past few years in bare weight is offset by the higher penalty of the cooling system, as compared with an air-cooled radial. There is, in fact, little to choose between the installed weight of high output engines of the air and liquid-cooled types, the lower bare weight of the liquid-cooled engine being offset by the higher weight of the installation.

If weight comparisons were made on the basis of unsupercharged engines the air-cooled type would show up to better advantage. The liquid-cooled engine has beaten the air-cooled type on bare weight, in fact, because it has been capable of using more boost. If designers of air-cooled engines had progressed faster on improved cooling, with cylinder heads of higher conductivity material, for instance, it is believed that the air-cooled engine would still be as superior in power-weight ratio as it was some six or seven years ago.

While there will undoubtedly be some reduction of specific weight of new engines, it is believed that this will be small, and the following figures, which can be regarded as being about the minimum possible at the present time, are useful as a rough guide to the future.

	Liquid Cooled.	Air Cooled.
Bare engine	1.00	1.15
Engine with cooling system	1.30	1.28
Total power plant less propellers ...	1.52	1.50

Fuel Consumption.

Now that the gas turbine is a proved possibility, builders of reciprocating engines will be harder put to it to keep pace, and this rivalry should prove extremely healthy; in much the same way as the competition between the reciprocating steam engine and the steam turbine proved beneficial to both types of prime mover.

In order to be successful, it is essential that the reciprocating engine should make the best use of the low fuel consumptions which are possible, as it is in this respect that the gas turbine will take some time to catch up. This being so, it will be necessary for builders of reciprocating engines to explore every avenue, such as high compression ratio, use of exhaust turbos, fuel injection, two speed propeller drives, etc. In conjunction with this it is equally important to reduce the drag of the engine by the use of the best possible installations, and it is encouraging that the engine builders in all countries have of late become more conscious of their responsibilities in this direction.

Power Plant and Installation.

The important step which was taken by the Air Ministry in 1938 in the setting up of a power plant committee, has already been referred to, and as a result of this, considerable strides have been made. It is hoped that the latest efforts of

our engineers in this direction will soon come to fruition, and that improved power plants will be in service before long. Although the power plants shown earlier in Figs. 50 and 51 go a long way towards the ideal, much remains to be done.

The advent of the gas turbine has shown how well this new form of prime mover can be installed, and unless the installation of the reciprocating engine is taken very seriously, in order to transform the highest possible percentage of engine B.H.P. into nett thrust H.P., it will be overtaken rapidly by the turbine.

The quickly detachable " standard " power plant will certainly remain with us for some years, for a large range of different types, but the demand for reduced drag will be such that the engines must eventually be completely buried, except on smaller machines with relatively thin wings. This retention of nacelles will prove to be a relic of the war developments, which have so far not yet succeeded, and probably will not do so before cessation of hostilities, in achieving the layout of power plant that the modern, clean aeroplane requires. The demands of war production are a definite deterrent to advanced thought and visionary design, the more so since prophetic ideas are liable to fade, or become stillborn unless facilities are promptly available for mock-up and prototype construction. The full fruits of a new conception in power plant layout, as with most other aero-

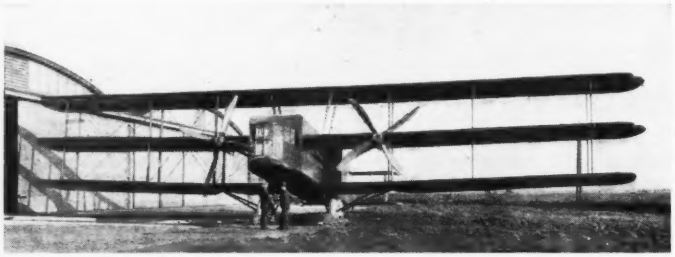


FIG. 71.

Bristol Tramp Experimental Triplane with buried Power Plant, 1922.

nautical projects, cannot be garnered until the original conception has been the subject of considerable research, followed by patient design and development. It has often been said, and I would repeat here that the time of individual artistry in aeronautics is passing rapidly, and the successful aircraft of the future, will in each case, be the product of an energetic team backed by research data.

So it will be with power plants, and the sooner this is generally realised, the quicker will we stop repeating again and again some of the errors of installation design that this war has revealed to be only too prevalent.

Looking at fighter type aircraft, the Bell " Airacobra " has definitely established that a long shaft drive to a remote reduction gear and propeller can be entirely satisfactory and, in fact, this machine has shown that in small sizes there need be no appreciable weight penalty for such an installation. Much further work has already been done in the development of angle gear boxes, etc, and it should therefore no longer be considered difficult to utilise buried engines with remote shaft drives of a varied assortment.

It is quite true that some difficult vibration problems are likely to be met, but these, it is suggested, can be reduced by the judicious application of hydraulic dampers, for instance, and a study of the torsional characteristics of the installation by using the various items of the latest test equipment which are now available, should readily overcome any such difficulties. It is significant that we in this country and also the Germans had buried engine shaft drive aircraft in

experimental operation immediately after the last war, and an example of this is given in Figs. 71 and 72, which show the Bristol " Tramp " triplane and the installation of four Siddeley " Puma " engines within its fuselage.

Reverting to fighter aircraft of the " Airacobra " type, and taking the scheme a stage further, the next logical step would be to instal one of the recent more powerful double crankshaft engines in a similar type of machine, still with remote drive to a counter-rotating propeller on the nose of the aeroplane. Fig. 73 shows the type of installation that can be envisaged, with separate extension shafts from each crankshaft taken to a contra-rotating reduction gear in the nose of the aircraft.

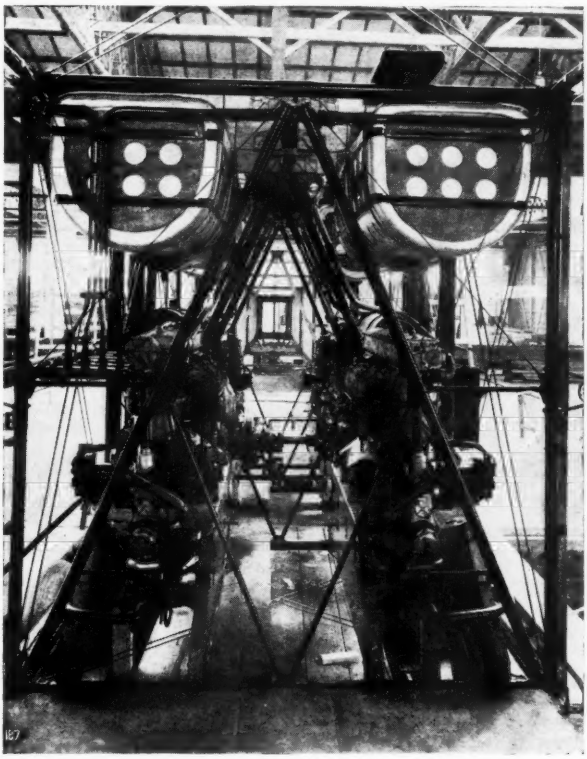


FIG. 72.
Internal view of Bristol Tramp, showing installation of Puma engines and shaft drives.

Considering an additional and more advanced step, there is another possibility for a long range fighter or mail plane, in joining, by means of gearing, a pair of high power air- or liquid-cooled engines together in the fuselage and driving to wing propellers through angle gear boxes. The type of machine which is envisaged would look something like that shown in Fig. 74, the two engines being arranged in tandem as shown diagrammatically in Fig. 75. Such an arrangement overcomes the objection to the interference which is inevitably caused by the three comparatively large projections of the fuselage and two engines on a thin low drag wing of about 60 ft. span.

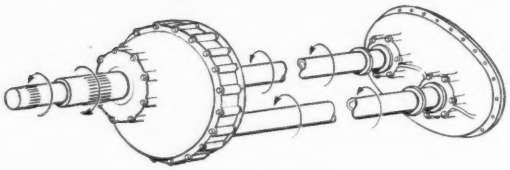


FIG. 73.

Extension shafts from double crankshaft engine to contra-rotating propeller gear.

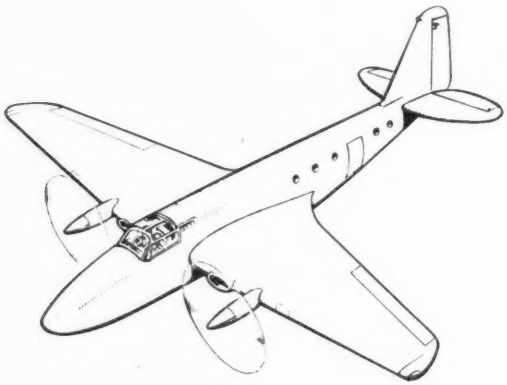


FIG. 74.

External view of long range aircraft with engines buried in the fuselage.

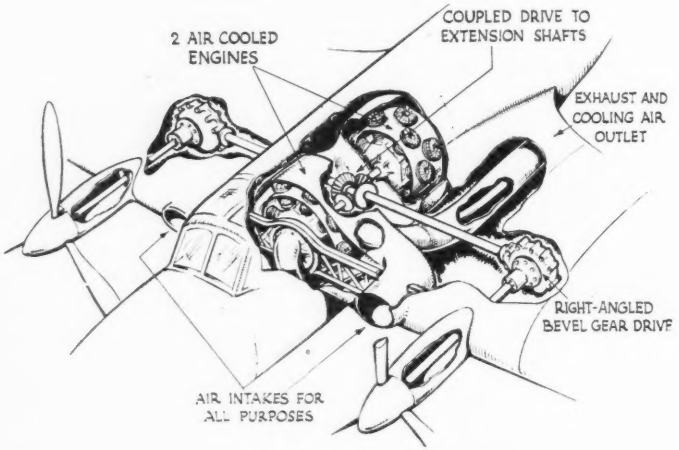

2 AIR COOLED ENGINES
COUPLED DRIVE TO EXTENSION SHAFTS
EXHAUST AND COOLING AIR OUTLET
RIGHT-ANGLED BEVEL GEAR DRIVE
AIR INTAKES FOR ALL PURPOSES

FIG. 75.

Cut-away perspective view of a pair of engines buried in the fuselage.

With an arrangement of this nature, there should be a considerable improvement in speed in comparison with the most carefully designed twin-engined machine using the same power plant with the conventional layout. The weight of the shafting and gear system would, it is submitted, be justified by the much reduced interference drag, particularly for long range work, as a built-in range in excess of 2,500 miles can be achieved. Further advantages as a fighter would be the improved manœuvrability due to the engine mass being concentrated at the C.G. of the aircraft, and the excellent visibility for the pilot and good armament layout.

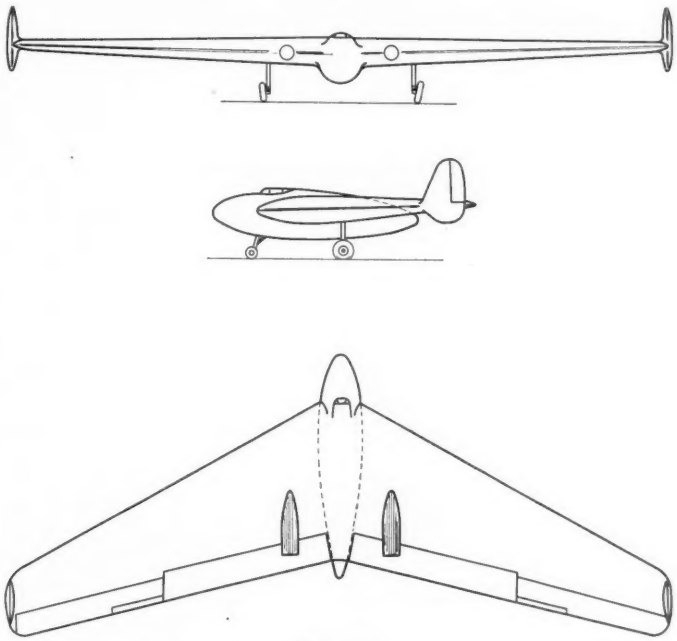


FIG. 76.

Diagram of jet-propelled mail plane.

One advantage of using a pair of engines grouped in this way for such a machine is that, if one engine is put out of action, the power of the other can be equally divided between the two airscrews. Alternatively, if the shafting on one side becomes damaged, full power can still be available from the other airscrew. The power plant could be so arranged, that maximum cruising economy and range are obtained with one engine only, and due to the better efficiency under these conditions, the range could be further extended by something like 10 per cent.

Recent developments in long range bombing operations have shown the necessity for high power, long range convoy fighters. Similar schemes with possible very high speeds, combined with long range, have already been suggested both in Britain and America, and although it might seem that, with the near approach of the turbine engine, such a design is redundant, this may not be the case, as it would have such a marked advantage on range over any other arrangement that can at present be envisaged.

Coming now to the larger types of multi-engined machines, it is apparent that the demand for reduced drag, to allow higher cruising speeds, will promote

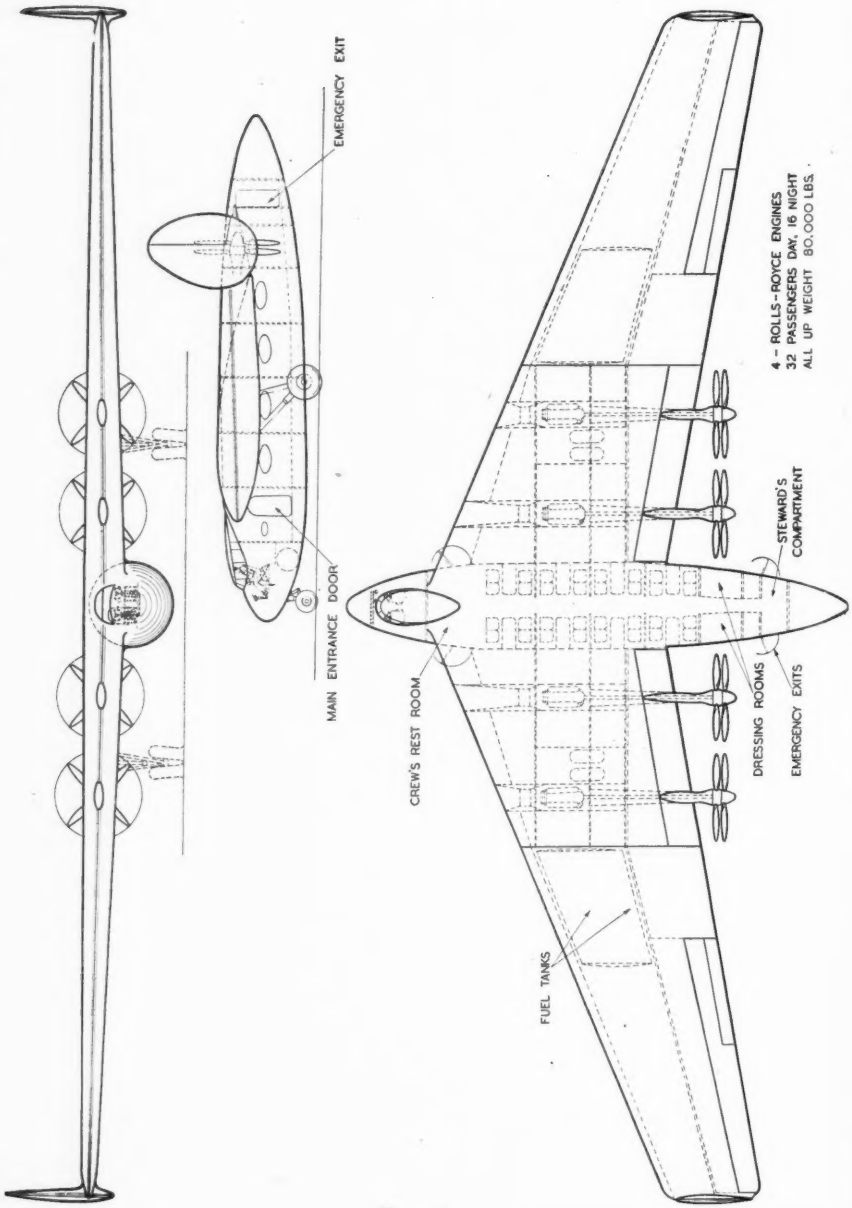


FIG. 77.

Diagram of 32-seater Flying Wing type of civil aircraft with buried piston engines.

increasing interest in the Flying Wing, and it is hoped that the necessary research work can be pushed ahead as rapidly as possible, so that one can envisage the practical realisation of this type in the not too distant future. Flying Wing aircraft will necessitate buried engines, which could be either air- or liquid-cooled, and the choice can only be made in the light of the particular design.

Figs. 76 and 77 show possible types of Flying Wing machines with buried power plants—the first a jet propelled mail plane, and the second a 32-seater civil type with liquid-cooled piston engines—in order to indicate the lines on which development may proceed. In any event the whole aircraft and engine installation will have to be the subject of considerable research, and the closest collaboration between the power plant and aircraft designer will be required before any finality can be envisaged. The problem of achieving this close contact satisfactorily in the future, which is so necessary to realise the right relationship between an airframe and its power plant, and to make the most rapid progress, is one worthy of almost any effort to find a practical solution.

The propulsive duct points the way to the final ideal, and although the power plant, as we are discussing it here, contains rotary machinery, the conception should be the same. There should, therefore, be one intake passage for all air flow, be it for the engine or for the cooling stream. Preferably also there should be only one exit orifice which will provide the maximum possible jet reaction, since it has already been demonstrated that regeneration of waste heat is perfectly feasible at the higher speeds of flight.

Considering the reciprocating engine-cum-propeller type of power plant, the desirable features can be outlined on the assumption that the unit forms a nacelle comprising part of a wing. Whether we consider the plant as a tractor or pusher does not make any material difference, since in each case an extension shaft will be advisable. We have, therefore, the following prime mover functions to cater for, involving the admission and rejection of working fluids and the orientation of mechanical units.

(i) Engine, generating shaft horse-power.
(ii) Cylinder cooling system, air or liquid.
(iii) Oil cooling system.
(iv) Exhaust gas disposal or utilisation for jet thrust or mechanical power.
(v) Torque conversion in the reduction gear.
(vi) Propeller thrust.

We are entering, through the medium of the gas turbine in aircraft, the era of ducts, and it is suggested that the future of the reciprocating engine will be realised to the full if it is admitted to co-partnership so far as ducted installation is concerned.

The basic principle to be aimed at in the fluid problems is that of straight flow from the entry to the exit. As visualised at present, the mechanism for boundary layer suction will involve a departure from straight flow through the power plant, but there will probably be some compensating advantages for the duct losses involved. Apart from the advent of boundary layer air entry therefore, we can stipulate full ramming intake, by-pass air-cleaners with automatic height control, fully regenerative waste heat systems, and lubrication systems freed from sludging and aeration, by the judicious use of full flow and by-pass filtration. Efficient engine pre-heating and press button automatic priming and starting will undoubtedly be two features required by aircraft operators.

As it may be some time before buried installations become a practical possibility for everyday machines, it is of great importance that equally careful thought should be given to orthodox installations. It is in the reduction of drag that the power plant designer will reap his great reward by diligent attention to detail. Having accepted the challenge of the fully ducted installation, he must then endeavour to place his mechanical units in a series layout with straight flow cooling. Internal

drag can be reduced, by low velocity flow and forced induction, to those units that demand a larger pressure drop than can otherwise be provided. New forms of construction using light alloy high conductivity materials will be developed for cooling matrices, and automatic control of air flow will be universally employed.

In military installations using pusher airscrews it might be convenient to install guns in the nose of the nacelle, with their vital parts behind the forwardly placed radiator, in the case of a liquid-cooled engine, where they will be protected from freezing.

Cowlings are one of the weak links in the chain so far as external drag is concerned, and although there is a welcome trend now to make these a real engineering job, it is to be hoped that in the future cowlings as we know them will disappear. For large civil aircraft at least, and possibly also on armoured military installations, the nacelle type power plants should have completely smooth surfaces with no protrusions other than the contra-rotating propeller, and no orifices besides an entry and exit for air flow. Such plants must represent the acme of reliability and efficiency. They will be removed complete from the aircraft for overhaul in the workshop at stated intervals. It is not believed that it is essential to insist on these intervals being greater than 700 and 800 hours, provided absolute reliability can be assured for this period, and provided a change of the power plant, complete with propeller, can be made in an hour. Apart from this work they should need no attention between overhauls, with the exception of three or four examinations of sparking plugs and filters. Obviously the longest practicable period between overhauls is highly desirable, and on the smaller engines longer intervals than have been suggested are already realised, but on big engines, it would seem a mistake to cramp design by attempting to extend the times too much.

I throw out this suggestion as a practical alternative to the conception of the fully accessible power plant, where the cowling hinges down to form working platforms and servicing work is attempted at frequent intervals. It cannot be conceived that really low drag structures can be built on this basis, nor will the accessibility of future engines be such that worthwhile servicing will be possible in the field.

In the generation of propulsive thrust from the waste heat, the mechanical problems attached to the appropriate installation of the cooling systems are not too difficult, and a short development period should suffice to point the way in any given power plant layout. So far as the exhaust gases are concerned there is much for them to do, ranging from direct ejector thrust to wing anti-icing, cabin heating and turbo supercharging.

The time is now ripe for a serious study to be made of the balance sheet of power plant operation on a heat basis, so that due value can be given to the various uses to which waste heat can be put for different types of aircraft. The results of such analyses are now some time overdue in our catalogue of power plant knowledge.

Engine Details and Components.

In the remainder of this section, brief notes follow on some of the more important points which I believe should receive attention in the development of the conventional piston engine of the future.

Flexible Engine Mountings.

The gas turbine should have advantages over the reciprocating engine in its smooth running, and this factor will undoubtedly encourage manufacturers to devote more time to a thorough technical investigation and the development of flexible engine mountings. This question of anti-vibratory mountings is not one to be undertaken lightly, and is definitely one for specialist treatment. It has been shown that a satisfactory rubber mounting for a 2,000 h.p. engine need weigh no more than 40 lbs. This whole question has not received the attention in

this country that it deserves, and up to the present time, it has been tackled in a more practical way in America. It is hoped that the attention that is now being focused on power plant will enable this problem to be more readily realised.

Blowers.

The subject of exhaust turbo superchargers versus mechanically driven multi-stage blowers will probably remain a question for contentious discussion. As speeds increase, the case for the exhaust turbo for military work becomes less strong, although it is felt to be of considerable importance for civil transport, and we know that, on the Fortress and Liberator, they have functioned very satisfactorily indeed during the war. These blowers are, however, somewhat crude in their design, particularly from the point of view of making a neat installation, but also from the aspect of the blower matching and the control of the turbo, and considerable improvements are to be expected. It is felt that this country has been very slow to appreciate fully the prize to be won from turbo superchargers, especially in view of our pioneer work, referred to earlier, and on large engines for long range civil machines, it will be impossible to ignore the loss of energy which a normal exhaust system involves.

The exhaust turbo supercharger lends itself to the multi-stage axial form of blower, and if all the experience which has been piled up can be utilised in the development of more efficient type in this country I believe it will be of great importance to use for post-war air transport.

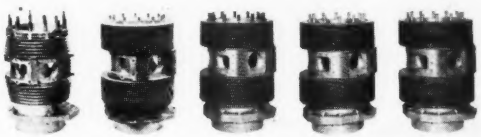


FIG. 78.

Comparison of finning on Bristol sleeve valve cylinders over the last ten years.

In order to make the best possible use of the turbo in reducing fuel consumption, it is essential that its characteristics should be carefully matched with the engine's performance at altitude, and that fully automatic controls should be employed. By this means it should be possible to achieve fuel consumptions as low as 0.36 to 0.34 lb./B.H.P./hr.

For mechanically driven blowers it is believed that the present interest in variable speed drives will be continued. The present arrangements with two-speed gears or with hydraulic slipping couplings work reasonably well, but cannot be considered to be the final solution, and there is much work to be done to achieve a compact and fool-proof variable speed solution.

Cylinder Cooling.

There is room for considerable further improvement in cylinder cooling, both on air- and liquid-cooled engines. In the case of liquid-cooled engines, it is anticipated that pressures in the cooling systems will be raised to allow an increase in the temperature and a consequent reduction in the radiator size. In conjunction with this it will be necessary to pay more attention to jets of cold liquid directed at those points where they are most needed, and it may well be that the time will

come when the addition of finning on critical internal parts of the cylinder will be beneficial.

Both in this country and in America the finning of air-cooled cylinders has developed to a fine art, and there is comparatively little to be gained by further decreases of the pitch of the fins or increase in depth. This means that further developments will have to be by means of higher conductivity materials. Although this is likely to arrive first for the cylinder head, it is quite possible that the barrel construction may also be changed to accommodate higher conductivity materials in the future. That the ultimate development of finning technique is being approached is well illustrated by Fig. 78, which shows the various stages of progress of Bristol sleeve valve cylinders over the last ten years.

Fan Cooling.

Although some work has already been done on the fan cooling of air-cooled radials, this has not yet been handled with the enthusiasm and vision which it warrants. Investigation started from the point of improving cooling on the ground, but it is now generally agreed that fans are also desirable for cooling under climbing conditions, particularly at high altitude, and it has been realised that the nett drag of a fan-cooled installation is likely to be lower than that of one relying entirely on gills or flaps to produce the necessary pressure difference. The present line of attack is to use aerofoil section multi blade fans running at about crankshaft speed, but these suffer from a number of disadvantages, the main one of which is the increase in power absorbed by the fan at low altitudes. Proposals have been put forward for reducing this penalty by using variable pitch stator rings, but it seems likely that other types of fan blading, such as those used for turbines, will prove more effective. In view of the expense and the length of time required for testing cooling fans under flight conditions, it will be necessary to undertake a considerable amount of small-scale and full-scale wind tunnel research in order to establish the necessary design data.

In order to reduce the weight and drag of liquid-cooled installations, it is rapidly becoming desirable to fan-cool these also, and it is believed that for the future all large aero engines will have cooling fans arranged in the cooling duct passages inside the envelope of the wing.

Engine Icing.

Weather conditions are still the main factor affecting regularity of air services, etc., and icing can be considered as the major hazard. If flying is to become an everyday affair, it is essential that this risk should be removed, not by palliatives such as have been adopted during the war, but by basic design. No ice-immune carburettor, either of the float chamber or bulk injection type, has yet been devised, and it is believed that the most straightforward method of attacking this problem is to adopt direct fuel injection.

Direct Fuel Injection.

Apart from the reduced risk of icing just mentioned, it would appear that material advantages are to be gained by the adoption of direct fuel injection. Many different reasons have been put forward as to why this system was adopted by the Germans, but it seems likely that the major consideration was that it enabled them to use home-produced fuels which could not be vaporized in a carburettor. If civil aviation is to be made really safe, it may well be that low flash point safety fuels will prove to be the solution, and these will demand direct injection.

It is not considered appropriate in a paper of this type to enter into the detailed technical arguments pro and con, but it is believed that for the future fuel injection should be regarded as a necessity. This applies not only to the large civil and military types, but also to the smallest unsupercharged transport types, whose distribution at present tends to become very indifferent at altitude.

Two-Speed Reduction Gears.

With high altitude flying, using turbo superchargers, the boost can be maintained at altitude at relatively low engine r.p.m., as opposed to mechanically-driven blowers even with two or more stages, where high r.p.m. are necessary to achieve this end, and where the power required for supercharging is such that the propeller shaft torque available for cruising at, say, 25,000 ft. will never exceed 55 per cent. to 60 per cent. of the take-off torque. The tabulation shown in Fig. 79 gives some indication of typical conditions for cruising at 25,000 ft. with single stage mechanically driven blowers and with turbo superchargers.

Condition.	Engine	Percentage of Take-off (R.P.M.)	Percentage of Take-off (Torque)
45% of take-off power	Mechanically driven blowers	86	52
	Turbo blowers	68	66
33% of take-off power	Mechanically driven blowers	68	48·5%
	Turbo blowers	50	66

FIG. 79.

Tabulation of cruising conditions at 25,000 feet with mechanically driven and exhaust turbo blowers.

With the low engine speeds and high torques which are possible for cruising at altitudes with the turbo supercharger, there is considerable incentive to the use of two-speed reduction gears, which allow an increase in propeller r.p.m. and efficiency for cruising.

Previous investigations have shown that, in general, the use of contra-rotating propellers is a more attractive method of obtaining improved all-round efficiency than the use of two-speed gears, and it has been felt that for this reason the first step is to develop these, and that two-speed gears will be the next step and will be used in conjunction with them. It has already been pointed out that, in order to hold its own in competition with the gas turbine, the reciprocating engine will have to give the very best possible fuel consumption, and it is only by such means as the two-speed counter-rotating propeller, that the consumption at high altitude can be maintained at a reasonable level. It is quite true that there are some engineers who will complain that the weight is prohibitive, but my only answer to them is that there were some people who made the same comment when variable pitch propellers were first advocated.

The gear problems involved in the development of two-speed counter-rotating drives are considerable, and it is suggested that the aero engine industry might, with advantage, consider using the resources of gear specialists. It is only by spreading the work involved amongst all the available competent specialist companies of various sorts that we can go fast enough in the development of our new engines.

A separate section of this paper is devoted to material developments, which are continually governing the progress of our engine technique, and certain lines of possible progress are suggested.

In the present section it would be out of place to discuss in detail the many possible engine component developments, but here again, as in the material problems, the technique is always changing and progressing, and there is ample scope for improvement of such items as piston cooling, piston ring technique, and sleeve and bearing design, to carry higher duties. The problems of ignition, starting and sparking plugs will be examined separately later in this paper.

SECTION 8.—MATERIALS USED IN AERO ENGINE MANUFACTURE AND POSSIBLE FUTURE DEVELOPMENT.

Materials have played an important part in the evolution of aero engines, and just as the aircraft designer has been dependent on the power plant manufacturer

for more powerful and lighter engines, in order to increase the performance of his aeroplane, so have the various improvements and the step up in performance of aero engines themselves, been closely bound up with, and to a considerable degree dependent upon, the introduction of new or improved materials.

The most important factor of all, however, in connection with aero engine materials has been, and still is, the improvement in technique of fabrication by the introduction of high precision methods, and minute care to eliminate porosity, inclusions, impurities and lack of consistency. In his Wilbur Wright Memorial Lecture of 1938 Gough gave a complete historical review of material developments for aircraft over a period of 35 years, and devoted a considerable portion of the paper to an exhaustive survey of the materials employed in the different types of aero engine.

In the early days of aero engine manufacture, before the last war, the pioneer designer was badly off in these respects, as compared with his successor to-day, and although quality is a relative term, the standard of forgings and castings supplied to the aero engine maker at the present time, as compared with 30 years ago, has greatly improved. Nevertheless, refinement in technique of fabrication remains the most important single factor in aero engine material, in order to improve and purify the constituent parts further, because these are having to operate under continuously high duty, with factors of safety considerably lower than is standard practice on contemporary stationary or automobile internal combustion engines.

Large quantity production must of necessity play a great part in making it possible to lay down sufficiently elaborate pattern and die equipment for the accurate fabrication of aero engine materials. When it is appreciated that as many aero engines are now made in this country in a few days as were constructed in a whole year about ten years ago, some idea of the background and experience that has been gained throughout the world as a result of the present war, on the specialisation of material fabrication, will be realised, just as much, in fact, as has been the case in the actual manufacturing technique of the engines themselves.

In the early part of this century, certain of the European countries went through a virile period in regard to the development of engineering materials, and were then more progressive than either England or America in certain respects. Some firms such as Vickers, Firth, Kayser-Ellison, in England, and Poldi, B.N.D., and Krupps, on the Continent, specialised on alloy steels, together with their forging and heat treatment technique for high class automobile parts such as gears, shafts, etc., and considerable strides were made in the strength, hardness and durability of these parts. This proved of great value for aero engine work in the last war.

During that war, a great deal of good work was accomplished in this country towards correlating, and putting on a proper footing, the various brands of steels used for aero engine manufacture. Methods of casting ingots, slabbing and slicing of billets, test pieces and analysis procedure were all laid down, while Air Board specifications were drawn up, and this whole matter put on a sound basis by a small band of enthusiasts, whose outstanding work has gone down to history. All this information was conveyed to America at the time. Heat resisting steels formed a bottle-neck, and considerable difficulty was experienced in coping with the valves of aero engines, towards the end of the war, due to poor fuel, and increases in b.h.p. and temperatures. Scaling and burning of valves and valve seats, was a serious problem, and valves would not stand up to more than a comparatively few hours' running at the powers and M.E.P.s that the engines were capable of developing.

Aluminium, which is now the principal material of aircraft construction, did not become available commercially until the close of the last century, and, despite the rapid development which took place in the use of light alloys, especially in

motor car production, the last war found it in a comparatively undeveloped state. It was not until 1911 that the age hardening phenomenon was discovered, and it is on this discovery that all the modern alloys for aero engine construction depend for their high strength properties. Thus, at the outbreak of the last war, none of the special high duty, high conductivity aluminium alloys, as we know them to-day, were available. Such castings as were being made in the unheat-treated alloys then available, suffered from rough and ready pattern making and casting technique, and the proportion of foundry scrap was very high, but even so, few, if any of the castings which were used in those days would have satisfied our present standards.

One of the most important applications found for aluminium alloys in this period was for pistons. At first, these followed automobile practice in the use of the old alloy containing 8 per cent. of copper. Later in the war, as a result of the research work carried on at the N.P.L. and other laboratories under the vigorous direction of Rosenhain, there was developed the first of the high strength age-hardening alloys to be evolved specially for aero engine components. This material, the well known Y alloy, gave excellent service for many years in the form of sand cast pistons.

All light alloy components were sand cast in those days, and gravity and pressure die castings in such materials were unknown; while the technique of forging the strong light alloys still awaited development. Even those sand castings, which were used in fairly large quantity, were not made with the modern benefit of accurate metal patterns, and pattern plates, regarded as essential to high accuracy and high production rates to-day. The same small group of people responsible for setting up ferrous standards, tackled the light alloy problems of standardisation with equal success.

The 20 years' period between the two wars has been one of the most fruitful periods of engineering material development, and the aero engine industry has led the field, in pressing for better and more consistent materials. On the whole, they have had a good response from the materials suppliers.

With the cessation of hostilities in 1918, the natural reaction of everybody wishing to get down to the urgent supply of ordinary engineering requirements, led to a stagnant period in the development of materials, just as the general interest in aero engine technique itself waned. Later on, however, as a moderate demand arose for higher powers and more efficient aero engines, certain progressive companies in this country appreciated the specialised demand for material for this purpose, and the support given by the Government to aero engine manufacture, provided an opportunity for these firms to make considerable advances in their material technique. This was especially pronounced in the case of the youthful light alloy industry, which in response to the urgent demands for greatly improved materials, concentrated most of its rapidly growing research facilities on the development of aircraft materials and their manufacture, and thus became, in effect, a part of the aircraft industry.

Turning to steels, during the ten to fifteen years prior to the war, considerable advances were made which have entirely changed the picture in regard to the wear, reliability and duty which could be expected with such important components as crankshafts, connecting rods, gearing, etc.

Mainly through the introduction of electric furnaces, and a finer technique in ingot production, testing and analysis, a fresh family of high duty aero engine steels of improved cleanness and consistency has been produced. The nitriding process, originated by Krupps in Germany, has been developed considerably in this country, and is now an everyday production procedure. The English Steel Corporation have pioneered the development of Hykro nitriding crankshaft stampings with an improved degree of cleanness with considerable success. This has been greatly assisted by the application of the immersion pyrometer, which is now widely used throughout this country.

The Firth and United Steels Groups have also specialised on high grade steels for aero engines, providing improvements in heat treatment, hardening and core strength, while other considerable improvements have been made by Firths, Kayser-Ellison and Hadfields in producing heat resisting steels, to such purpose that the modern poppet valve has long life, running at continuously high temperatures, in combination with sodium cooling and stellite surfacing.

During the period between the two wars, there was considerable progress in the development of light alloys having special combinations of properties required for aero engine components. Among the major difficulties met with in the early post-war years in aero engine development, were those due to the deterioration in the strength of light alloys at the operating temperatures encountered in modern aero engines. Other difficulties are due to the lack of absolute uniformity of the materials of the components themselves, a factor which was thrown into high relief by the low factors of safety prevailing in this new branch of mechanical engineering.

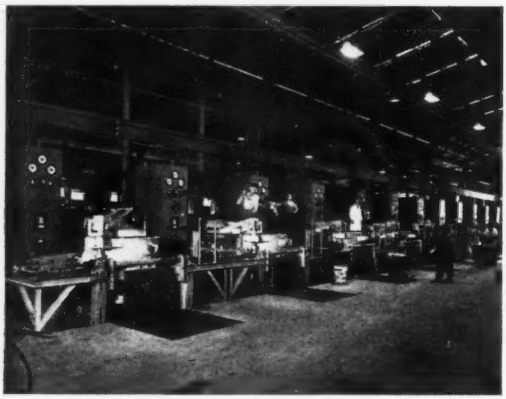


FIG. 80.

Battery of low frequency furnaces at High Duty Alloys, Ltd.

To cope with these problems, the forging of the light alloys, which previously had been used only in the form of sand castings, became imperative. It is not within the scope of this paper to go into details of the obstacles which had to be overcome in developing a forging technique for these low-melting point materials, which were considerably harder at the highest temperature, to which they could safely be heated, than is steel at its forging temperature. For surmounting many of these difficulties and for pioneering the commercial production of light alloy forgings, credit must go to Devereux and his associates, who solved the problem by the development of a technique which extended right through, from the casting of forging billets, to the control of forging and heat treatment temperatures to an accuracy not previously attained. Fig. 80 shows a battery of low frequency furnaces used in the manufacture of high quality light alloys.

By these new methods, pistons, radial engine crankcases, cylinder heads and sleeve valve cylinders for radial air-cooled engines reduction gear housings and other important highly stressed parts, were all developed for production from light alloy drop forgings. This new technique was pioneered in this country with specially developed processes and equipment with considerable success.

The Rolls Royce Company made a valuable contribution to light alloys for aero engines by the invention in their laboratories of casting and forging alloys

of considerably better properties than those previously available. The development and manufacture of these R.R. alloys was taken up by Devereux's company, High Duty Alloys, Ltd., and the forging technique which they had developed was brought to a high pitch of accuracy and consistency for quantity production, special emphasis being given to the production of pistons.

On the casting side, compared with other countries, we have been slow in the past to appreciate the commercial as well as the technical value of spending money on high quality foundry equipment. The indispensability of first class metal patterns and pattern plates, of special foundry tackle, and of precision checking and testing equipment for inspecting castings before machining, is now realised, but this was far from being the case only a few years ago. The great strides made in recent years in the pattern equipment, in moulding technique, in sand control, in die casting and X-ray and other inspection and testing aids, has provided us with far sounder and more dimensionally accurate castings than were available a comparatively short time ago.

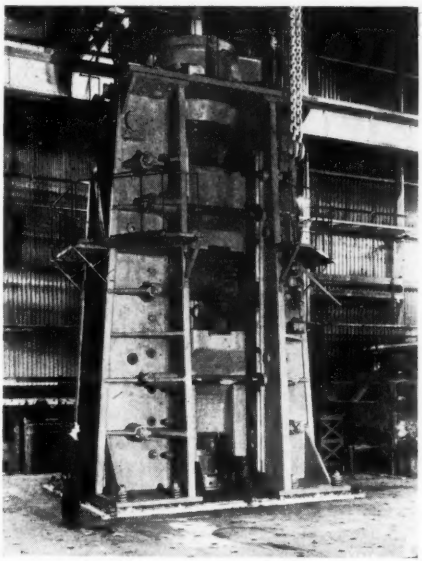


FIG. 81.

25-ton double-acting stamp at English Steel Corporation for making aero engine crankshafts.

In between the two wars, magnesium alloys came into use for aero engine components. Germany particularly, has been in the forefront with this development, not only to save weight, but also from an economic point of view, and the German technique was quickly followed up in Italy. An appreciable proportion of the castings of the present wartime American aero engines is of magnesium alloy. The magnesium development in this country has not been a happy one and there have been changes of official policy, owing to the difficulties in obtaining sufficient raw material. It is suggested that had there been generally in all countries interested in aero engine development, a more far-seeing policy on both sides in regard to the application of the family of magnesium alloys, we should be farther along the road than we are to-day.

It is believed that there has not been enough intelligent collaboration between the engine firms and the makers of castings. There has, in certain circumstances, been a tendency to select the wrong application, thus bringing into relief the bad qualities of the material, while there has not always been a sufficiently realistic outlook by the foundry side, as to what had to be faced up to in aero engine work. Owing to its special characteristics, magnesium should be used in as thick sections as possible, and where this can be accomplished with the right foundry technique from the initiation of the project, and with enough patience brought to bear on the problem, good results can be obtained.

During the last five years the materials suppliers have been strained to the utmost, building up supplies for the enormous war production of aero engines. In the first year or so of the war, the shortage of certain materials was critical, and light alloys were in a particularly serious condition, but by determined effort, and good organisation, these difficulties have all been overcome.

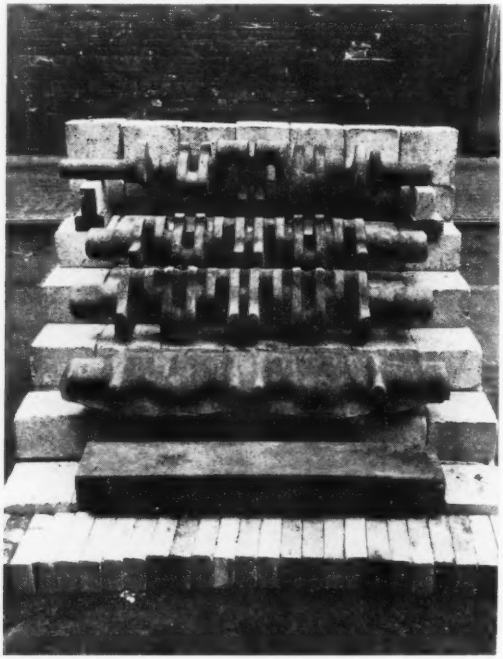


FIG. 82.

Merlin crankshaft stampings in different stages of manufacture.

Illustrative of the latest equipment employed on aero engine stampings, Figs. 81 and 82 show the latest 25-ton hammer employed in the English Steel Corporation works on the production of Merlin crankshafts, together with the crankshaft stamping in various stages of production, while Fig. 83 shows the 22-ton hammer at the High Duty Alloys plant for the production of large radial engine crankcases.

The aero engine material position to-day is a happy one, from a production point of view, but the great urge for quantity production has inevitably thrown a considerable strain on the raw material fabricating industry as a whole, which has entailed a static condition in regard to the development of new and improved

materials throughout the country, and in view of the advances that are anticipated, it is hoped that we shall see some rapid steps forward as soon as is feasible after the war.

It is suggested that there will be an urgent need after the war for suppliers to produce improved materials for aero engines, which will generally help the breed, deal with certain specific difficulties, which are being met at the moment, and enable higher output and greater reliability to be obtained. While asking for still better material, there is also the question of cost, which is going to be of primary importance after the war, when we shall be faced with keen competition. It is felt that the cost of some of our aero engine materials is in excess of what it should be, and that in certain directions the whole matter requires careful consideration. This is a broad question affecting the whole of the raw materials industries, starting from power and coal production, through the producers of the primary metals, iron, aluminium and magnesium, to the steel and light alloy fabricating industries, and cannot be divorced from the technical aspect of future development. If this country is to maintain its position in the forefront after the war, it is believed that producers of steel, aluminium and magnesium must approach this whole subject with vision, and be determined to supply the aero engine industry with raw materials at prices which will enable them to compete fairly with other industrial countries.

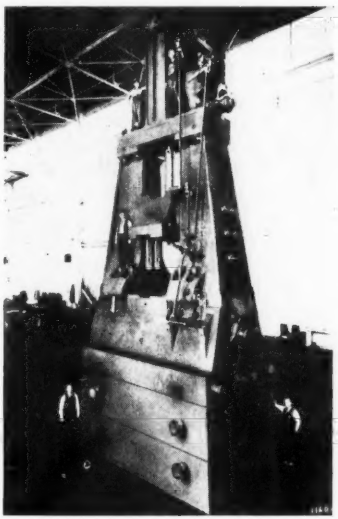


FIG. 83.

22-ton hammer at High Duty Alloys Ltd. for making aero engine crankcases.

One of the important aspects of the post-war materials problem is the necessity for a clear policy from the Government, in regard to new developments, and the laying down of the necessary research equipment for work to proceed as soon as it is possible to do so. It is also most desirable that there should be closer collaboration between engine makers and materials suppliers, as it is only in this way that the latter can appreciate fully all the problems that are at issue. In the past, these contacts have not always been as good as they might have been, and anomalies and misunderstandings have from time to time arisen. This

need never have been so, and when we have time to review the situation dispassionately after the war, we must ensure that all such difficulties are smoothed out, if we are going to meet competition and make the rapid advances we are looking for.

With regard to steels, although the dream of an aero engine designer is always to find a material with a better modulus, harder surface, and greater fatigue range, it is not expected that we shall see very startling developments during the next ten to fifteen years. There is, however, always the possibility of some unforeseen discovery, and since, therefore, it is difficult to predict with any accuracy what may happen during this period, it is only possible to indicate the trends, on the basis of our present knowledge.

Two interesting applications of the nitriding process have so far played an important part in the evolution of the modern high performance aero engine. First is the development of high strength chrome molybdenum steels, together with a suitable nitrogen hardening technique, whereby the fatigue strength of machined components is substantially increased, especially at fillets, changes of section and surface irregularities, while, at the same time, the suitability of the steels to run under heavy loads in contact with bearing alloys is much improved. The second is the technique of nitrogen hardening the surface of the high alloy heat resisting steels used for valves and sleeves, materials which differ substantially from those for which the nitriding process was first developed.

It is thought that we shall see a greater use of nitrided steels, that improvements in them should continue to be sought, and that, by modifications in the composition and heat treatment, the core strength should be maintained during the nitriding operation. It is most important to develop these steels, so that distortion and internal stresses are eliminated to the utmost. A high impact value is also required after heat treatment, a condition which, at present, is not consistent with high core strength. A possible way of obtaining the latter may be to put the surface into compression by means of the shot blasting process.

At the present time S.82 and S.90 appear to be the most popular case hardening steels, but we shall require something better, and we may see some form of case hardened Hykro coming to the fore.

Earlier in the paper I have recommended that it would be a good policy to concentrate our future piston engine development on types using the Burt McCollum sleeve valve mechanism, which would put sleeve valve material and technique on the highest priority. If this course of action should be adopted, there is ample opportunity, and indeed necessity, to explore, on high priority, new materials and methods for sleeve materials.

After several years' intensive development, I was responsible for guiding a policy which enabled this country to produce satisfactory sleeve valve engines. In their present form, N.C.M. centrifuged castings and forgings, nitrided and honed are employed. However, I am only too conscious that this process is not by any means the final answer, and there are opportunities for further improvements. The heat differential between the piston and cylinder, via the sleeve, is of the order of 40-50°C., clearly bringing out the limitations of this material from a conductivity point of view, although it is good from expansion, hardness and wear aspects. Another point in connection with this sleeve material is its cost of manufacture in man hours.

It is hoped to see a big drive made after the war to develop new materials for sleeves, which will retain the present advantages of the existing type in regard to hardness and expansion, but which are better from a conductivity point of view, and are lighter and cheaper to produce. There are several interesting lines of attack, but such developments take a long time—possibly several years—to bring fruition, and there is no time to be lost.

The whole aero engine world is watching with great interest the improvements that the steel maker may be able to make in heat resisting steels. The last

war saw a serious bottle-neck on valve steels, and if we can make the same step-up in the first few years after this war with heat-resisting materials as was realised on valve steels after the last, then it is thought that we may expect to see important developments on the exhaust turbo and the gas turbine. As temperatures in excess of 850° may be required, it may be that materials of the essentially non-ferrous type are more likely to fill the bill. In any case there is a big reward to be reaped for intensive development along these lines.

We have had considerable contributions to the improvement of steels by the introduction of the Fox inclusion and grain counts, and the development of creep testing technique under temperature conditions. The aero engine fraternity deplores the recent passing of Dr. Hatfield, of the Firth Brown laboratories, the dynamic chairman of the Sheffield Technical Advisory Committee, and many will recall the two papers he read before the Society on " Ferrous Metallurgy for Aero Engines " in 1917 and 1934. We shall require for the future, all possible initiative and vision from the British steel industry to maintain our lead in the aircraft power plant field.

Light alloys will play an increasingly important part in aircraft power plant developments in the future. During the fifteen years prior to the war, considerable strides were made by the producers of light alloy components for British aero engines, and it is believed that there is the vision and research capacity in this country, and given the necessary encouragement and a clear picture of what is wanted we shall be well qualified to meet future demands.

Up to the present time, light alloy castings have been used mostly for in-line engines, all pistons, of course, being forgings, while wrought materials have been employed for the main components of radial engines. Such a procedure will undoubtedly continue for the future, but with the step-up in the size of piston engines, and the higher specific outputs which we may expect, the question of the right medium to employ for such items as crankcases, and whether to rely on improved aluminium alloys, or better quality and thicker scantling magnesium alloys, is one for considerable thought. There has been some question of replacing light alloy materials by steel drop forgings or welded steel construction for crankcases, when we get on to the promised new fuels, and certain radial engine makers in America have already done this, but I do not consider it to be a good solution.

Reference must be made to the importance of internal stresses, and their distribution in relation to the performance of light alloy components. It is now generally recognised that those forms of heat treatment which result in the highest static strength properties in the finished component, do not necessarily give a product possessing the best properties for long life under the conditions prevailing in the engine, and that, in many cases, advantage is gained by the use of treatments which result in somewhat lower static strength properties, but yield a product in which the internal stresses are of a low order. This observation is, indeed, not surprising in the light of our increasing knowledge of the effect of mean tensile stresses on the fatigue range. On the matter of research into the internal stress in light alloy components, acknowledgment must be made of the splendid work of the late Dr. Fromer and his colleagues in developing X-ray methods. Fig. 84 shows the X-ray apparatus used for the determination of internal stresses in a radial engine crankcase by means of crystallography.

One further improvement is suggested to the light alloy materials manufacturer as being necessary. I am told that it is basically impossible of accomplishment, but as the industry has already brought to successful fruition for the aero engine maker so many material developments which they thought to be impossible, I think we should not accept this one as falling within that category. I refer to the important question of being able to surface harden light alloy materials. If it were possible by some suitable treatment to raise the surface hardness of aluminium

forgings at working temperatures appreciably, it might enable us to employ light alloys for such parts as sleeves, to improve the surfaces of piston skirts, and to open up a new vista generally for piston engine development.

With the introduction of gas turbines, forged light alloy and cast magnesium alloy will both play important parts, and just as we have seen advances in impellor, piston and crankcase forgings during the last ten years, so we may also expect to see a similar step-up in the technique of drum forgings for turbines and improved impellors. Shortly after the war it is hoped that we may anticipate the introduction of an improved family of light alloy materials for forging, with greater strength and hardness at elevated temperatures, the latter being most important, as well as considerable improvements in magnesium alloys.

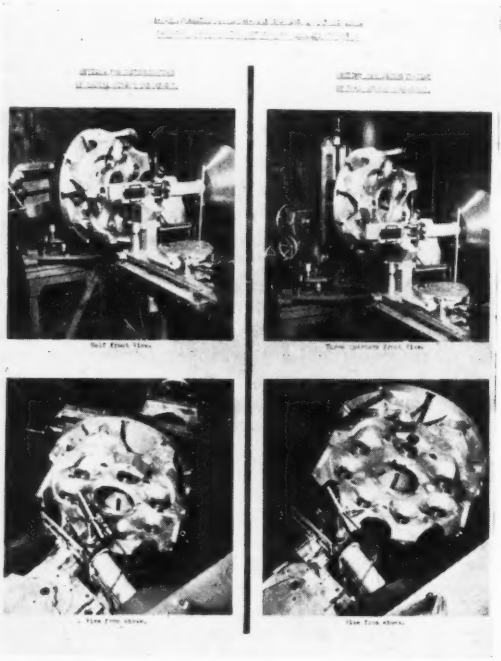


FIG. 84.

Crystallographic apparatus at High Duty Alloys Ltd. Laboratories, showing Radial engine crankcase under observation.

If the improvements in magnesium which are at present envisaged in the project stage can be realised in production, this will have a considerable effect on aero engine technique, and will alter the proportion of magnesium used in future aircraft power plants to no small extent. Much work, however, has to be accomplished to eliminate the present deleterious effects on magnesium, which, at anything above 100-130°C., make it quite unsuitable for application to engine components, owing to the softening and pasting of the surfaces of the material. There are also the problems of sub-microscopic porosity, which have been a source of recurring trouble, all of which require patient development work. Weight for

weight, magnesium provides a stiffness unknown in any other material, clearly postulating its use in the most massive way possible.

One other development I would like to refer to is powder metallurgy. This is an interesting new material technique, which has been chiefly sponsored in America up to the present time, and which I had the opportunity of investigating for the first time in some detail, during our mission's visit there in the spring of 1943. The development of this new process places a new tool in the hands of the material manufacturers, which may well enable them, by its proper development and use, to meet some of the demands for improved properties. In the future, openings can be seen for this process for the manufacture of piston rings, valve seats, valve guides, sleeve balls, pump gears, etc. These parts can be made to size without subsequent machining, and owing to their density should be ideal for heat conductivity. During the first few years it is anticipated that powder metallurgy will be employed only for these relatively small components, with no subsequent machining and special physical properties.

Looking farther into the future, it may also be possible to produce new alloys, which of their refractory nature, cannot be produced by any other means, such as high silicon content, aluminium silicon, or tungsten silver. It may also be possible to produce various alloys of high purity and rigid analysis. Still later on we may see improved developments of plastics, impregnated with various metal powders, which might be used for bearings. Alloy steel parts with excellent qualities, such as cams and tappets, might be produced. It might also be possible to produce hard facings for cylinder bores or sleeves by powder metallurgy technique.

Whereas it is expected that we shall see many new developments in the improvement of the physical properties of all materials for aero engines, there should be ever before us the all important need and urge to go forward with the advancement of manufacturing technique, thus attaining a more consistent and higher standard, and at the same time encouraging the abolition of locked up stresses to the very utmost.

Finally, there is another important factor which will contribute increasingly to the more rapid development of materials and their proper utilisation, and that is in the field of testing, where engineering and material development go hand in hand. It has been the practice, especially in engine development, where temperature adds further complication to already highly complicated mechanical design problems, to do most of the testing the hard way, *i.e.*, by subjecting designs and materials to tests under actual service conditions and advancing design by the study of failures. This is a tedious and expensive method. The present tendency is towards reproducing service conditions artificially in the laboratory, although results must eventually be confirmed by practical tests. Advances may be expected during the next five or ten years in methods of component testing based on increasingly accurate methods of stress analysis. Particularly applicable in power plant work are stress indicating lacquers, special extensometers, electric strain gauges, photo elasticity, X-ray crystal analysis and methods of detecting flaws by means of supersonic vibrations, or by the determination of damping characteristics. Moreover, time-consuming fatigue and creep testing may be superseded by damping measurements under precisely controlled conditions. The development and application of such new tools as these will add greatly to our knowledge, and will enable the rate of progress to be speeded up very considerably.

A comprehensive stress investigation will include both dynamic and static aspects, the former to establish the mode and magnitude of operating loads, and the latter to evaluate the corresponding stresses. That these developments are proceeding rapidly is evidenced by the details published in the past year. Some details of the X-ray stress analysis work carried out by High Duty Alloys, Ltd., and of the damping research by that company and the Firth-Brown laboratories, have been published recently, indicating the lines along which the pioneer material research workers are proceeding.

SECTION 9—ANCILLARY EQUIPMENT.

In order to secure a high degree of simplicity and reliability, there should be the fewest possible varieties of ancillary services and methods of operation, both for engines and aircraft requirements which have to be derived initially from the power plant. The aim should be to minimise the number of engine drives for all ancillary services.

At the same time there is a decided trend to use electric actuation for a number of the aircraft and engine services. It is therefore submitted for serious consideration, as a future policy, to fit a suitable modern design of electrical generator on a single direct drive feeding new types of rugged and compact motors, instead of the numerous outlets hitherto provided on auxiliary gear boxes.

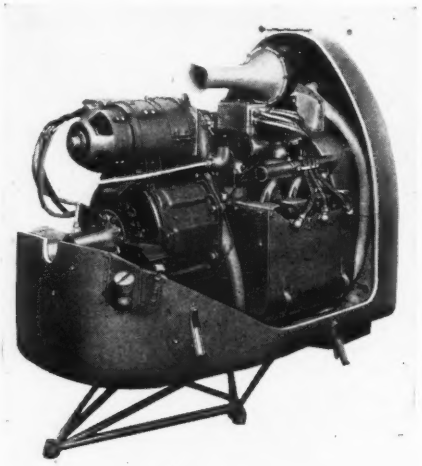


FIG. 85.

Rotol 60 h.p. Auxiliary Generating Plant self-contained unit.

Future Ancillary Power System.

To get the right picture for long term policy, it is necessary to consider briefly what the future electrical system may be. The general adoption of three phase alternating current at 400 cycles per second and at a pressure up to 200 volts, is visualised on account of the need to cater for the widest possible range of size and type of aircraft, including long endurance and high altitude operation. It is of prime importance to eliminate commutators and brush gear which are the principal limiting features in the design, performance, reliability and compactness of aircraft generators and motors, and it is now practicable to build machines for relatively high speeds with solid rotors and fire-proof stationary windings capable of withstanding high working temperatures and overloads. Such machines weigh only about half that of previous direct current types and maintenance is reduced to merely that for ball bearings.

On large, or very large aircraft, the practice would be to fit either a 12 kw. or 24 kw. alternating current generator on each of four power units.

Apart from fuel injection, ignition, superchargers and probably oil pumps, all other services could satisfactorily be operated with simple induction motors running proportionately to engine speeds.

Auxiliary Generating Plant.

It has become recognised that in the future, except in the case of small aircraft, an auxiliary generating plant will form a necessary part of the aircraft equipment. This would be carried for use on the ground when out of reach of local supply sets, and as a standby against failure of main engines alternators at take-off or for emergency at landing or moderate altitudes in flight. The A.G.P. should be fitted with the same size and type of generator as that on the main engines. In the case of flying boats it might be necessary to carry two such units to give augmented power supply when on the water. The unit should be readily detachable for replacement in servicing or for alternative cargo, particularly on short journeys.

A British design by Rotol is shown in Fig. 85. For requirements associated with a transitionary stage in the development of an electrically equipped aircraft, this set has both a d.c. and a.c. generator and in several respects is therefore larger than would be the case with the standby sets contemplated for the future, which would be of approximately 20 and 40 b.h.p. respectively for 12 and 24 kw. alternators.

The A.G.P. would function as a standby for a constant voltage supply for lights, instruments and radio, under the conditions mentioned, in addition to forming the emergency supply for those services taking power from the main engine alternators.

Turbine Drive for Ancillary Power.

It is possible to visualise future operation of electrical generators by gas turbines which will afford improvements in efficiency and weight by taking advantage of the ability to run alternators at 24,000 r.p.m. Such turbines would normally be operated in flight from exhaust gas waste energy and be adapted for independent combustion for emergency and ground use.

Ancillary Power Balance Sheet.

The whole question of utilisation of waste power in long range aircraft is a matter to which insufficient study has yet been given, hence a critical balance sheet should be drawn up to determine how the whole range of ancillary services should derive their power. To secure maximum flying endurance for the weight of equipment and fuel carried should be the aim to be achieved.

Ignition.

It has been pointed out earlier that the ignition system of petrol engines still remains one of the most serious weaknesses in aircraft. Efforts have lately been directed to the development of an ignition system which would give an enhanced and more reliable performance, particularly at high altitude, and ability to overcome the causes and effects of plug fouling and erosion. Research and development are active in America, chiefly aimed at the improvement of materials for distributors, harness and design of insulation generally, and improved low tension systems, and in Britain in a rather more radical approach in the investigation of possible high frequency systems. In such systems a condenser is charged to a suitable potential and discharged through a spark gap and transformer into a high frequency circuit.

Various types of circuit arrangement have been tried, and it has been established that, within existing limits of equipment, insulation, etc., an increase of some 20 per cent. in plug voltage can be obtained at frequencies of the order of three megacycles per second and a similar, or even greater, increase of distributor voltage can be obtained up to 50,000 ft. on high frequency as compared with present performance up to 35,000 ft.

It is also found that under the usual circuit conditions the degree of plug fouling which reduces the effective resistances across the electrode points can be allowed to go much further while using quite a low series resistor. These improvements allow plugs with a shorter insulator leakage path to be used, designed to run cooler and generally more suitable for high boost and high temperature conditions.

Carburettors and Injection Systems.

Carburettors have, until comparatively recently, been characterised by the use of choke controlled metering of the fuel flow, and the limitations of this system in its various forms and designs are well known. Much effort and development, however, has made the aero carburettor a reasonably reliable instrument, but it has suffered complication in the general control and supercharging functions which play an important part in the modern power unit.

Limitations in the amount of air which can be passed through the choke have focused attention on other means of introducing the fuel into the air stream. The introduction of a fuel metering principle in which the engine itself acts as the air flow meter, and fuel flow is controlled to accord with the engine speed, boost pressure, temperature of the charge entering the cylinder, and the exhaust back pressure, has undoubtedly provided a greatly improved solution to the problem, irrespective of whether the ultimate injection of the fuel is accomplished at the inlet to the supercharger or directly into the cylinder. This basic system has made possible a direct realisation of the ice-immune induction system, together with elimination of the upper limit of altitude imposed by the choke controlled method.

Direct injection of fuel, whether it be high performance safety fuel or the normal low flash point grades, is the right line to work upon for the large multi-cylinder engine as the solution to the distribution problem, and here again there should be no difficulty about its early realisation in conjunction with the R.A.E. control system. It remains to select the most suitable form of pump and injection system, with the best possible layout for the particular engine, in such a way that it is compact and accessible for easy changing as a unit, at the same time avoiding all chance of aeration.

Starters.

The cranking of the larger modern engines has brought serious problems, and we are facing limitations in several directions. The limit for plain direct current motor starters, has, it is submitted, been reached at round about 2,000 h.p. engines in current use. A new vista is, however, opened up by the application of the combined inertia and direct cranking system in which the energy drawn by the motor is spread over a longer period. Present successful operation of this type encourages development for the larger engines of the next period ahead. This starter will be applicable both to alternating current in the future and to direct current in the meantime.

It is also visualised that a combined starter-alternator may be developed, so that use can be made of the larger machine with an extra reduction gear for cranking, and with the saving of the separate starter-motor.

An alternative to electric starting is the use of a small petrol engine which, for the short period required, can be made small enough to be geared to the main engine in the normal manner. There is no apparent limitation in starter power in this direction as compared with other forms of combustion starting.

For future large power plants, the battle for supremacy will therefore be waged between starter-alternator on the one hand and individual high speed I.C. starting engine of from 15-80 b.h.p., on the other hand, which will also provide a margin for pre-heating. It has been shown that of all the forms of energy that can be harnessed in practical form—such as electrical, explosive, chemical, and liquid fuel, the most efficient, on a weight basis comprising the substance and its container, is liquid hydrocarbon fuel. The figure of 80 b.h.p. is mentioned as a reasonable upper limit in the next ten years, because the very large gas turbines of axial flow types likely to emerge will require considerable starting effort owing to their particular characteristics. The normal jet type engine will, of course, not need such powers, but the matter should not be overlooked, and I commend the I.C. engine as the ultimate direct starter unit.

One must not omit the possibility of a smaller gas turbine auxiliary being interposed between the basic starter unit and the main engine, be it ultra large turbine plant or a reciprocating unit up to, say, 6,000 h.p. The fundamental theorem is the stepping up of moderate press-button controlled electrical or internal combustion power in stages until the main unit can be started.

Testing Equipment and Technique.

In dealing with materials reference has already been made to the increasing degree of instrumentation, and electro-physical technique which will play an important part in the detail development of highly stressed parts of engines and power plant installation.

Side by side with these developments in detail strength testing and vibration, are others involved in the rig testing and flight trials of power plant. Owing to the cost involved in both materials and personnel in such running, it is important that the maximum of information should be obtained from every hour of development testing whether on the test bed or in flight. To this end extensive installations of thermo-couple circuits with recording potentiometers, and miniature pressure heads and manometer boards for photographic records of temperature and pressures in all parts of the installation are required to furnish full information on power plant conditions and performance in relation to flight data obtained by simultaneous observations and automatic recording. This work opens up a large field of activity calling for new type equipment and personnel not yet fully envisaged in this country. Moreover, a large measure of instrumentation will play an important part in the successful development of gas turbine and jet engines.

Section 10.—Propellers.

Historical Survey.

Propellers, although strictly in the realm of the aircraft designer, when considering the aircraft as a whole, are nevertheless of great importance to the power plant designer, and have always, in the past, been one of those difficult " betwixt and between " problems of turning B.H.P. from the prime mover into effective thrust through the medium of the air, entailing a combined aerodynamic and mechanical solution. It is chiefly for this reason that the ideal combination of propeller and power plant has not always been achieved. During the last war it would be correct to say that two-bladed wooden propellers and, in a few instances, two-piece four-bladers, were standard practice in the Air Forces of all the combatants. As has so often happened in other branches of aeronautics, we in this country pioneered both metal blades and the variable pitch propeller. Even during the last war we were actively experimenting with variable pitch devices, and in the autumn of 1918 satisfactory flight tests were made at the R.A.E. with a four-blade variable pitch propeller fitted to an R.A.F. engine with turbo supercharger in an R.E.8 aircraft. Wooden blades with a metal hub centre were employed and the weight of the complete unit was 85 lb., some 50 lb. heavier than the equivalent wooden conventional type. The installation is shown in Fig. 86. Shortly after the war successful hollow steel blades were developed by Watts, and in 1924 patents for a fully automatic constant speed hydraulic propeller were applied for by Hele-Shaw in association with Beacham. Both of these devices were flown successfully within the next few years. The first installation appears to have been in a Gloster " Guan " machine with a turbo supercharged Napier Lion engine in 1927, and a photograph of this is shown in Fig. 87. Subsequently, also in 1927, a successful 250 hours' flight test was completed in a Gloster " Grebe " aircraft with a Jupiter engine. This installation is shown in Fig. 88. After this, little interest was taken in the design for many years, but much credit is due to the Gloster Company, and later the Bristol and Rotol Companies, for continuing its development despite many setbacks.

To America, however, must be given the credit for appreciating the practical value of the variable pitch propeller, and the fact that the extra weight paid good dividends, providing the machine had the correct wing and power loading. Prior to this realisation, the Americans had also developed experimentally and

FIG. 86.

Variable Pitch Airscrew in R.E.8 aircraft tested at Farnborough, November, 1918.

FIG. 87.

Hele-Shaw constant speed hydraulic airscrew in Gloster "Guan" with Napier Lion and exhaust turbo, 1927.

brought to a production stage a light alloy metal propeller. This propeller was first used with considerable success in the Schneider Cup of 1925, which was won by U.S.A. with a Curtiss engine, propeller and aircraft combination. This was a one-piece blade twisted from thick duralumin sheet, but three-blade propellers with steel hub and detachable duralumin blades followed quickly, it being found that the cyclic effect of the three-blader was advantageous as regards smooth

running and in improving the slipstream over the fuselage and tail. The Americans, with this detachable metal blade experience behind them, were therefore able to change over to the variable pitch control mechanism on their standardised metal propellers more easily than was the case in this country, in spite of the pioneer work of Hele-Shaw, Watt, Lynam and others. The low wing, clean monoplane passenger aircraft developed in America in the early 1930's, with comparatively high wing loading, demanded variable pitch propellers to enable them to operate at optimum efficiency, and this contributed to a considerable degree in establishing this type of propeller on a production basis.

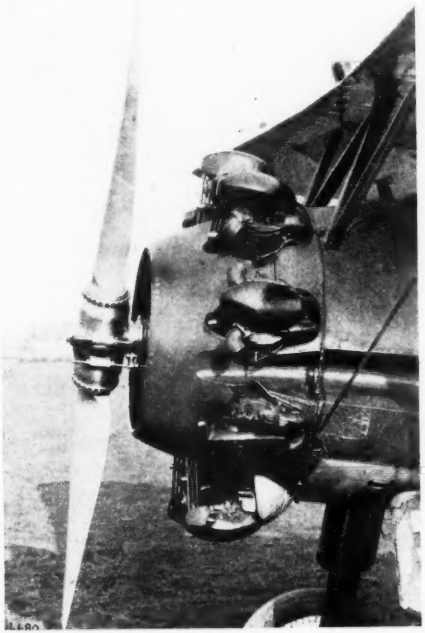


FIG. 88.

Hele-Shaw constant speed hydraulic airscrew in Gloster "Grebe" with Jupiter engine, 1928.

Propeller Position at the Outbreak of War.

The war found this country only partly adapted to variable pitch propellers. The twin-engine bombers, with air-cooled radials, were all fitted with three-blade two-pitch or constant speed variable pitch propellers of American origin manufactured by de Havilland, and certain liquid-cooled twin-engine bombers were equipped with early Rotol constant speed propellers, whereas many of our fighters with liquid-cooled in-line engines were still using two-blade wooden propellers. By 1940, however, the fighter situation was changing, and many Hurricanes and Spitfires were fitted with de Havilland two-position propellers.

It was in the spring of 1940 that an event occurred, the significance of which began to be felt in the critical days of the Battle of Britain. This was the introduction into full-scale production, by the Rotol Company, of the variable pitch

propeller initially designed by Hele-Shaw, and developed over such a long period of years without coming to fruition. A number of these propellers were quickly brought into use, and a start was also made on the conversion of remaining two-position type to the de Havilland/Hamilton constant speed system. Both of these developments gave our fighters a greatly improved performance in the " nick of time." Since that time all our fighting machines have been fitted with variable pitch constant speed propellers.

Improvements in the propeller in regard to the number of blades, the pitch change mechanism, spinners, etc., have just kept pace with the increase in power and rated altitude of the engines. The requirements of the R.A.F. have been completely met by two propeller Companies, viz., Messrs. de Havilland, who took out a licence for the American Hamilton designs, but who have subsequently developed these along their own lines, and Messrs. Rotol, who took over the Hele-Shaw designs and also secured a licence for the Curtiss electrically operated type.

Another fortunate step in regard to propeller development in this country which, in the early days of the war, was of immense value to our supply problem, was the introduction into the Rotol propeller of a detachable compressed wood blade. Curiously enough, this was a German invention, the rights of which were acquired in this country two to three years before the war. It has been more highly developed here than in Germany, and when in the early years of the war we had not sufficient press and hammer capacity to provide enough of the large aluminium forgings for all the variable pitch propellers required, its introduction in a refined form undoubtedly " saved the day." The improved technique in compressed wood blades has just about kept pace in performance with duralumin. They further have the advantage of being appreciably lighter and good from a damping point of view. The propellers on all present British military aircraft are fully automatic, constant speed, three- or four-bladers, with either forged light alloy or compressed wood blades.

Propeller Efficiency and Weights for High Powered Engines.

Increases in speed and height with the conventional piston engine makes the problem of propeller design and efficiency progressively more difficult, and at speeds of about 550 m.p.h. at 20,000 ft. it is debatable, in the present state of the art, if conventional propeller-driven aircraft are practicable. Fig. 89 shows the drop in performance with height and speed. The specific weight and complexity of propellers has also increased steadily from the simple two-bladed fixed pitch wood airscrew of fifteen years ago for 500 h.p. to the complex contra-rotating airscrews for engines of 2,000 h.p. and over of the present time. Fig. 90 illustrates by means of a curve the increase in weight with progressive increments in power. In actual practice the introduction of the four-bladed propeller showed little or no weight increase over the three-blade propeller for a given power, this being achieved by taking full advantage, in the four-blade design, of development in the strength of blade roots which had been going on at war-time pace, wherein smaller root diameters were made possible, with attendant reduction in hub and overall propeller weight.

As this whole question becomes more complex, so does it become necessary to link the propeller more closely with the power plant. So much is this the case that experiments of merging the technical and industrial interests of the power plant and propeller into one organisation or group have already been made in different countries. In the case of the gas turbine this is absolutely essential, and there is no doubt that the advent of the latter has caused us to think furiously about realising the better combination between the power plant and the propeller on the conventional piston engine. How far this marriage can prosper will have a considerable effect on the continuity and future success of the piston engine. However, by whatever means it may best be accomplished, there is not the least doubt that, for the future, there must be considerably closer collaboration between the engine maker and the propeller manufacturer, and a better mutual

understanding of all the problems involved, if we are to see development along the best lines. It is interesting to note that the latest tendency in some quarters is for the propeller designer to make his product a completely self-contained unit, with all operating services incorporated. Although this may appear at first thought to be contrary to the idea of closer collaboration, it is a move to be

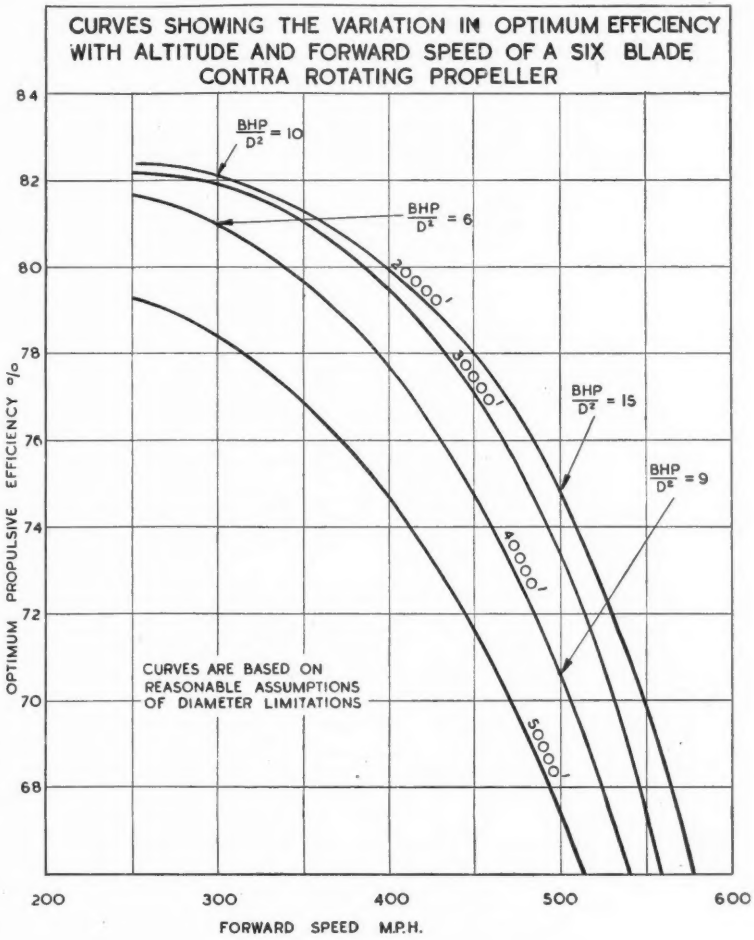


FIG. 89.

Curve showing propeller performance with height and speed.

encouraged, since, from the engine designer's point of view, the problem of providing an adequate oil system for propeller actuation, without upsetting or being affected by the engine lubricating system, is a very real one.

Such major mechanical problems on the engine as two-speed gears and contra-rotating gears to accommodate the requirements of high power, high performance aircraft, as well as built-in controllable fan cooling for air-cooled engines to give

adequate cooling under climbing conditions near the ground as well as at altitude, all tend to complicate the hub portion of a variable pitch propeller. The centre portion of the present-day type, comprising the hub, spinner and blade roots, is, in certain cases, unsatisfactory from an aerodynamic point of view and needs considerable refinement. The maximum number of blades in current operational

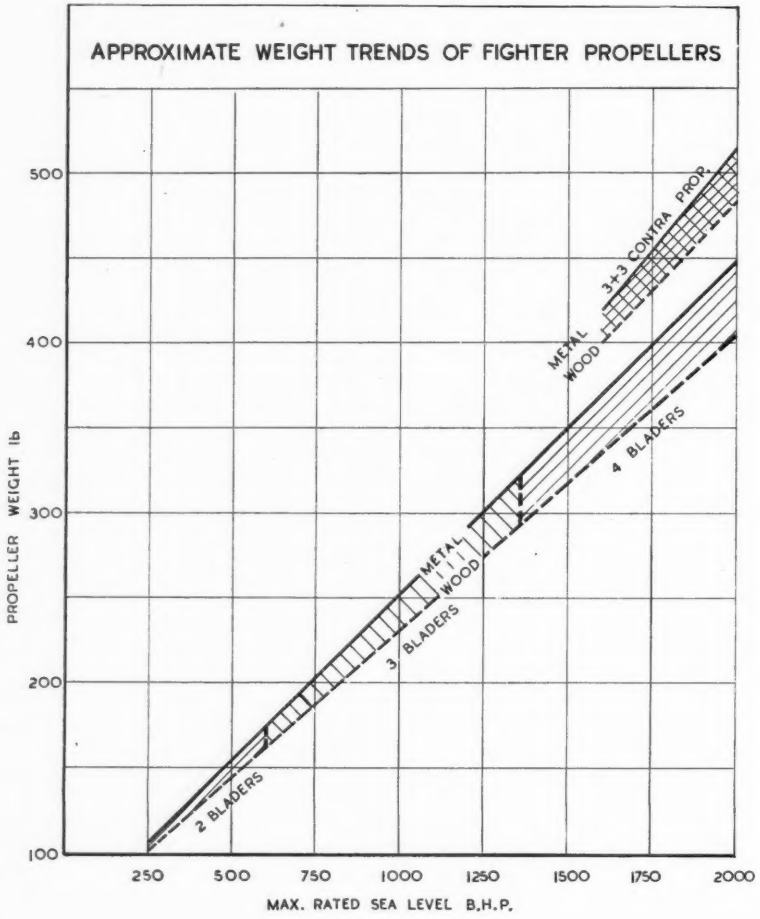


FIG. 90.

Curve showing increase of propeller weight with increment of power.

use in a single hub so far is four. As engine powers increase, however, we can expect to see hubs with a larger number of blades, for while the top speed performance can be catered for with four blades, the diameter restrictions give poor take-off and climb. A five-bladed propeller would not increase top speed performance, but would give a much improved take-off and climb. At the present time the limiting features governing the number of blades in a single hub are both aerodynamic and structural.

Single-rotation, multi-bladed, high-power propellers are somewhat of a problem at take-off, where undue swing is generally becoming evident. This is one of the important reasons why contra-rotating propellers are now receiving so much attention throughout the world. There are, of course, other basic advantages, such as improved efficiency, compared with the equivalent single-rotation type (same diameter, same number of blades), absence of trim changes in the air while manœuvring, etc.

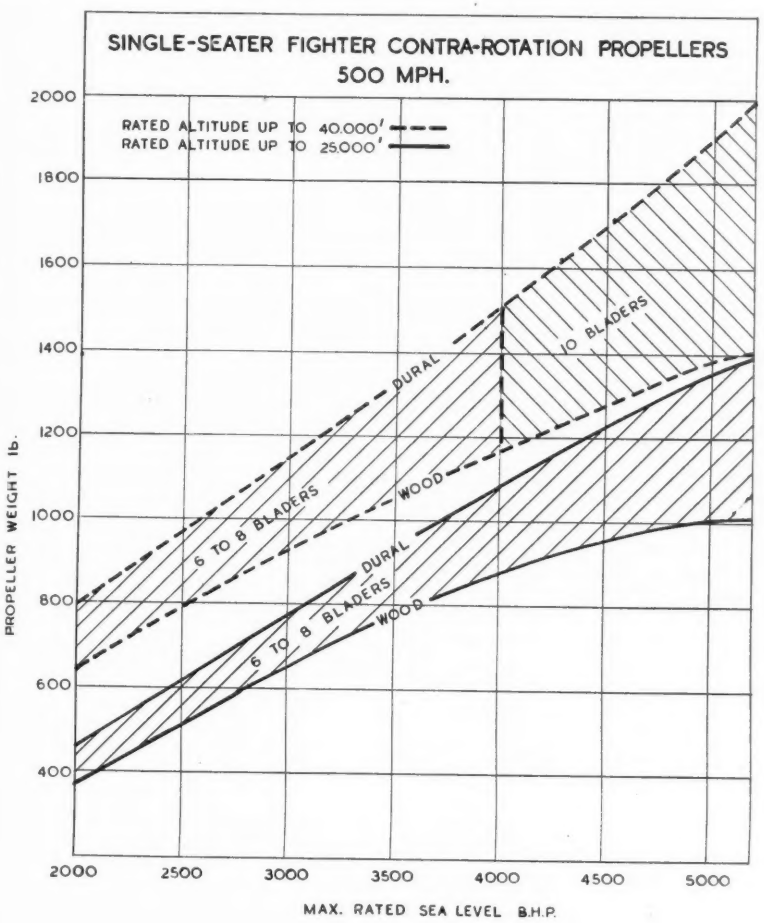


FIG. 91.

Increase in propeller weight with power-curve for fighters.

In a previous section proposals have been put forward for the lines of development of the piston engine until 1960, and suggesting that we shall be ready for piston engines of 5,000 h.p. as soon as they can be developed. A propeller which is designed to absorb a given power at ground level is capable of dealing with only a quarter of that power at 40,000 feet, owing to the decreased density of the air. Nevertheless, it is anticipated that contra-rotating airscrews will be

developed to meet the requirements of 5,000 h.p. engines at altitude by the time these engines are ready. This, however, means steady development and careful thought to prevent undue increases in complication and weight.

Weight factors are of the utmost importance on variable pitch propellers with piston engines, and Figs. 91 and 92 show the estimated increase in weight and

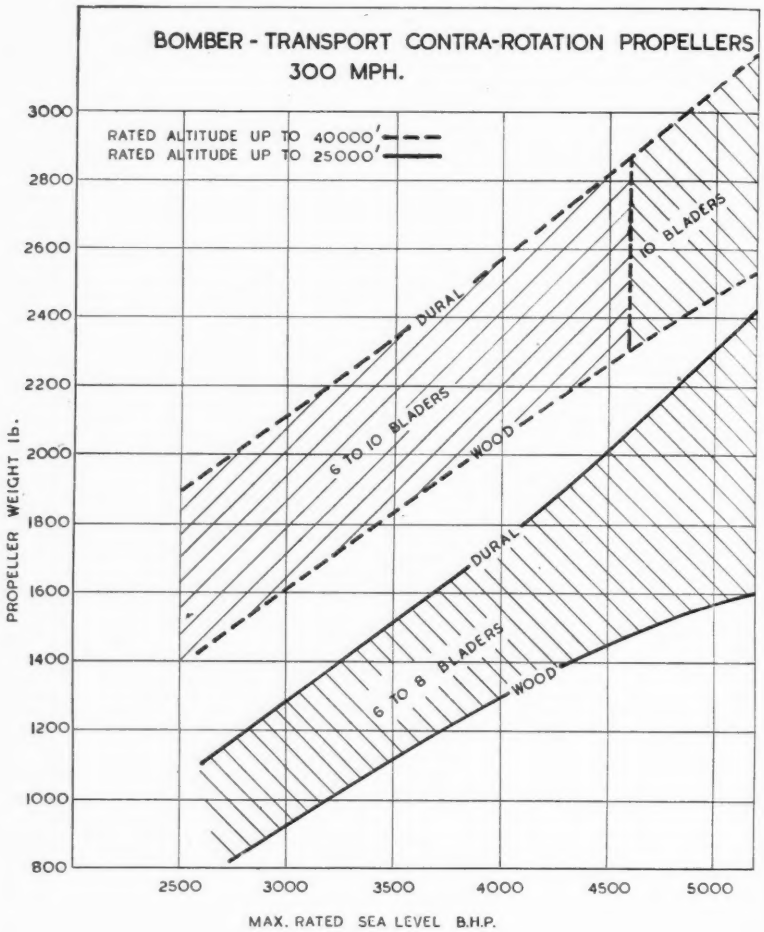


FIG. 92.

Increase in propeller weight with power-curve for bombers.

number of blades for powers from 2,000 to 5,000 h.p. On these curves the fighter class with a diameter of 14 to 16 ft., and the bomber/transport class with a maximum of 22 ft., have been considered. It is suggested that here is a case where official guidance and help early enough in the life of the engine development can be of considerable value to the propeller designer.

Propeller Operating System and Materials.

There is still much to be done to find a satisfactory solution for the high-power multi-bladed contra-rotating propeller, in regard to the neatest, lightest and most efficient hub mechanism, and both hydraulic and electrical operation have been explored. Whereas for the general ancillary services of the aircraft it is likely that electrical systems are going ahead and will probably oust hydraulics, on the other hand, in the case of propellers, there would seem to be much to be said for retaining hydraulics with the oil system completely separated from the main engine lubrication.

The question of blades is one of great importance, and there is every opportunity for initiative and good design to cut down the weight of the blades and roots. A great deal of work has been carried out both in Germany and in this country on magnesium blades, but with the present alloys the notch-sensitivity and softness of the material preclude its successful use. On the heavy transport or bomber class of aircraft of the future, the present type of light alloy solid blade would seem to be getting near the end of its term, especially since these machines, in the sizes we may expect to see, will undoubtedly be equipped with contra-rotating propellers with anything up to 10 blades (five per bank). It is considered that from a weight aspect, the solid duralumin blade will be able to hold its own for diameters up to 15 ft., but above this it will become increasingly important to consider lighter blade types. Alternatives are compressed wood, hollow duralumin and hollow steel.

America has done much useful work on steel blades, and eventually these may prove to be the ideal solution, owing to their strength, durability and robustness. Solid steel blades with thin sections could probably be kept within reasonable bounds of weight, were it not for the torsional oscillations which are prevalent, and which are becoming an increasingly difficult problem on high-power reciprocating engines. With the ever-increasing speeds at higher altitudes it becomes more and more essential that the propeller blade should be designed from pure aerodynamic considerations, and not be hampered by being compelled to have its aerofoils sufficiently thick to keep down the vibratory stresses induced from the engine system. Further, the propeller hub weight is correspondingly reduced. This is such a serious problem that it may be necessary to consider, in spite of the weight limitation, the introduction of some form of hydraulic or spring damper between the propeller and the engine to deal with these vibrations, which can have a serious fatigue effect on the blades.

The hollow steel blade suggests a more radical solution than the solid type, and a great deal of work in this direction has already been done in America. In the past, however, manufacturing technique has not been sufficiently refined to permit the attainment of good aerodynamic design, but more recent developments have gone far to remove this state of affairs, and there is little doubt that we shall see a more widespread use of this type in the comparatively near future.

There is much work to be done on the development of the propeller for the piston engine in the next ten to fifteen years, and, as already stated, how ingeniously this is tackled will determine the future life of the reciprocating engine.

Propellers for Jet Engines.

The propulsive efficiency of the reaction jet is largely governed by the forward speed of the aircraft. To overcome the relatively low efficiency at low speeds where the take-off and climb performance are not comparable with airscrew propulsion, it would appear essential to supplement the jet with thrust augmentors, either in the form of ducted fans or propellers. Theoretical investigation indicates that a propeller would give better efficiency on take-off and climb than would the optimum ducted fan. This lower efficiency of the ducted fan is accounted for by the limitations on the diameters for which it is practical to design, necessitating high rotational speeds and several stages in order to absorb the power. Further, it would seem that for operation at 20,000 ft., for example, the orthodox propeller

is superior up to speeds of 450 m.p.h., while the pure jet comes into its own above 550 m.p.h., giving the ducted fan only a narrow band between 450 and 550 m.p.h. in which to justify itself. At each end of this range it would be in competition with either the airscrew or the pure jet. Thus the application of the ducted fan will have to be carefully considered in conjunction with specific installations, but it is possible that, with development, there will be considerable scope for the use of this form of thrust augmentor.

A further advantage in using a propeller would be the provision of negative thrust by reversing the pitch of the blades which could be utilised to act as a brake for either diving or landing conditions, according to the type of aircraft. With the three-wheel undercarriage, where, on landing, the drag of the machine is considerably less than for the normal type with a tail wheel, the reverse pitch propeller may prove invaluable for reducing landing run, and there is no doubt that it will be widely used for this purpose.

Summary of Propeller Requirements for the Future.

1. With the increasing complication and mechanical development necessary on modern quick pitch change propellers it is necessary to standardise a basic design which can be used on a wide range of propeller sizes. Interchangeability of parts to the utmost degree is an important design consideration.

2. It is necessary to envisage engine cooling fans as an integral built-in portion of controllable pitch propeller design from the inception of the type.

3. Specific propeller weights are becoming so serious with increased powers that every effort must be made, both in blade and hub design, to achieve an appreciable saving in the weight of the whole propeller.

4. The inner sections of the hub and blades are in urgent need of re-design and refinement to improve general efficiency.

5. With increasing powers and weights, the question of balance and the elimination of vibration is becoming daily more important. It has been universally established that the present practice of static balancing is by no means sufficient, and aerodynamic balancing has become essential to reduce vibration. This vibration is the result of unequal " thrusting " of the propeller blades, due mainly to manufacturing tolerances. Aerodynamic balancing has obviated the necessity for normal dyanmic balancing, and is much more simple to carry out, as well as being more effective.

6. A considerable increase of range of the mechanism and speed of pitch change up to 40 degrees per second will be required in future, and adequate pitch range will be necessary for feathering and braking. The use of the propeller in negative pitch as an addition to the normal braking services is becoming a reality, and this is valuable for application to dive-bombers, thereby reducing flap dimensions, and also to heavy bombers as a landing brake, thus lessening landing run and tyre wear. For normal constant speeding, rates of pitch change of the present order of 8 to 10 degrees per second may suffice, but even so, it may be advantageous to increase the feathering rate to around 15 to 20 degrees per second. Attention must be given to means of locking the blades in fixed pitch in the event of breakdown of the controlling mechanism of the propeller.

7. Adequate de-icing must be incorporated for the blades, spinners and fans, and also serious consideration must be given to the operating system under low temperature/high altitude conditions.

8. Tests will be required to investigate the effect of compressibility, e.g., by pressure plotting across aerofoils and blades, and by tests on propellers both in the wind tunnel and in flight.

9. Various other investigations covering the measurement of thrust and torque for braking conditions, the vibration aspects of pusher contra-rotating airscrews, and the pitch distributions, will be required.

The above list by no means covers the complete field, but gives some indication of the magnitude and scope of the work which must be embarked upon, and the necessity for providing adequate research equipment and facilities, both in regard to tunnels and to full-scale flight testing. The exploration of the airscrew for high-power, high-performance aircraft has now become a major undertaking, almost equal in importance and length and cost of development to the power plant itself. Without the suitable equipment and the financial resources it will be impossible to achieve sufficient results to keep pace with engine and airframe development. It is of the utmost importance that all this work should be tackled on an adequate priority and that engine and propeller makers should keep in the closest touch with each other.

Section 11.—Future Policy on Gas Turbines and Jet Propulsion Power Plant

All of us are now aware that certain vital developments are taking place with the long-sought-after internal combustion turbine. The previous sections of this paper have dealt only with the development of piston engines, and there is little doubt that the rapid progress which has been made in this country with the gas turbine has been a great spur to the piston engine. The protagonists of the latter are certainly alive to the possibilities offered by the turbine, and a keen competition will ensue over the next four to five years, and it will be interesting to see what will be the outcome. It is appreciated that the gas turbine must eventually take the lead, but it will depend upon the energy and drive of the reciprocating engine enthusiasts as to how long this latter form of prime mover can maintain its supremacy. There is at present considerable divergence of opinion regarding this matter; I lean to the view that it must be a fairly slow change.

The main disadvantage of the gas turbine jet propulsion engine appears to be its high fuel consumption, and it must be remembered that there is still much scope for reducing the specific fuel consumption and drag of the piston engine, with improved fuels and better power plant layouts. Improvement in fuel consumption of the gas turbine would not appear at present to be bound up with the characteristics of the fuel itself, and it would seem that the task of achieving economic operation of the turbine rests almost entirely in the hands of the development engineer and designer, whereas with the piston engine the designer must to a large extent work to the limitations imposed by the state of fuel technology.

However, there can no longer be any doubt in our minds that there are many outstanding features on the gas turbine which render its application for aircraft propulsion particularly attractive.

It is therefore proposed in this section to give a broad view of what has been accomplished to date, and what we may expect for the future. It must be appreciated that in the interests of secrecy and security it is impossible to disclose the more intimate details of the mechanical designs which are being pursued, or the performance figures which have actually been obtained, but nevertheless it is possible even at this stage to present sufficient evidence derived from basic features and fundamental principles to allow a general appreciation of the potentialities of the continuous combustion turbine power plant.

History.

Investigation into the possibilities of the internal combustion turbine in its various forms has been carried out by a number of authorities over a period of more than thirty years, although in point of fact one of the earliest recorded suggestions for a gas turbine power plant was put forward in a patent taken out in 1791 by an Englishman named John Barber. Many years later, numerous attempts were made to obtain useful work from compressor and turbine combinations, but these usually resulted in the building of units which had barely enough margin of power to overcome friction of bearings and windage losses, etc., in the turbine and compressor.

Much energy was devoted by Holswarth, in Germany, from 1905 onwards to various turbine schemes using intermittent combustion. A number of industrial units were subsequently built, and though this work has some bearing on more recent successful developments, no application of such machinery for aircraft propulsion was considered.

Probably the earliest useful application of the gas turbine is attributable to Messrs. Brown Boveri of Switzerland, who patented machines which were driven by the hot catylyst gases from the Houdry petroleum cracking plants in America. Subsequently work was carried out by Meyer on the installation of a Brown Boveri turbine in a locomotive, and among other industrial machines a 4,000 K.W. generating plant has been erected at Neuchatel.

The gas turbine has also been seriously developed in a secondary role for internal combustion engine supercharging, but as the history of the development of the turbo blower has been dealt with briefly earlier in this paper, no more than a passing reference need be made here. Though high efficiency of the turbine for such units has not been demanded, by virtue of their application, the problems of materials have had to be faced, and recent developments in this field have had a direct bearing on the progress of the gas turbine as a prime mover. It is probably true to say that the turbo blower has not been more widely adopted in the past due to the relatively poor performance of the blower units produced and because of the unsatisfactory way in which the installation problems have been tackled.

However, little progress was made with the gas turbine as a prime mover in the aircraft field until comparatively recently, mainly due to the limitations imposed by the materials available, but partly due to insufficient background on high efficiency compressor and turbine design factors. The appreciation of the principles of vehicle propulsion by means of a reaction jet also dates back to pre-twentieth century times, though little general interest was aroused in the aircraft world until the Italians publicly announced their achievements with the Caproni-Campini jet-propelled monoplane.

The possibilities of rocket propulsion were seriously investigated in 1927 to 1929 by Von Opel, who, it will be remembered, met his death in an accident with one of his machines.

Great Britain has taken a leading part in the application of the gas turbine to aircraft propulsion, through the efforts of workers at the Royal Aircraft Establishment, who in 1928 initiated certain basic experiments on axial flow compressors and turbines, while a year or two later Group Captain Whittle took out patents, commenced investigations, and did all in his power to interest people in the application of the jet-propulsion engine to aircraft. It was not until 1937 that the Aeronautical Research Committee was sufficiently confident to recommend that full-scale developments of gas turbine engines at public expense should be initiated. After this, work went ahead at the Royal Aircraft Establishment and Power Jets, in co-operation with certain firms associated with the manufacture of turbines.

There is no doubt that this country has established a permanent place for herself in the history of the development of this new prime mover, and we owe a debt of gratitude to Group Captain Whittle and his colleagues, and also the R.A.E. and the firms who have co-operated, for the vision and effort which has been demanded to overcome the difficulties and disappointments which have preceded the practical application of the continuous combustion turbine power plant.

We in Great Britain must not forget, however, that extensive developments on gas turbines and jet propulsion are taking place on the Continent and in America, and it is important that we should not rest on our laurels, but show the same resourcefulness and initiative in bringing our successful prototypes to regular series production as we have evinced during the initial stages of development.

Every effort should be made to encourage the development and manufacture of different types, and the aircraft manufacturers must co-operate by providing suitable machines for the flight testing of these new prime movers.

Technical Review.

Turning now to the technical principles governing the operation of the gas turbine, in order to obtain a clear picture it is best to deal with the specific applica-

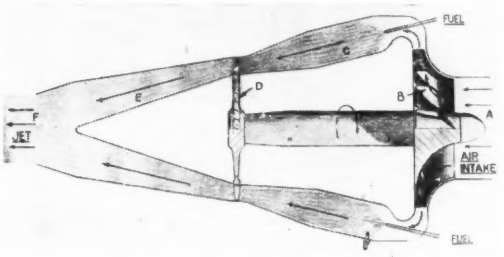
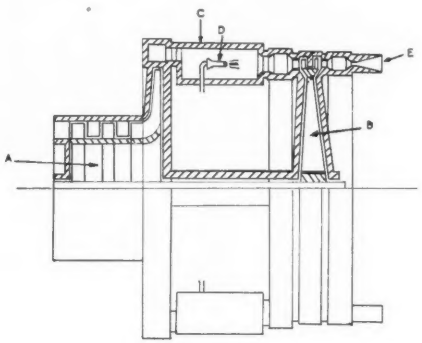


FIG. 93.

Diagram showing main features of jet-propulsion unit.



A. COMPRESSOR ROTOR.
B. TURBINE ROTOR.
C. COMBUSTION CHAMBER.
D FUEL JET.
E DISCHARGE NOZZLE.

FIG. 94

Outline diagram from original Whittle Patent specification, showing axial flow compressor.

tion of the various forms of this prime mover under the following separate headings:—

(*a*) The pure jet-propulsion turbine unit.
(*b*) The combined jet and propeller turbine unit.
(*c*) The composite piston engine-turbine unit, using jet and propeller.

Dealing with (*a*), Fig. 93 shows the main features of the power unit. Air is led from the intake A, under full ram due to the forward speed of the aircraft, to the compressor B, from whence it passes to the combustion chamber C. Only a certain proportion of the compressed air is mixed with the fuel for combustion

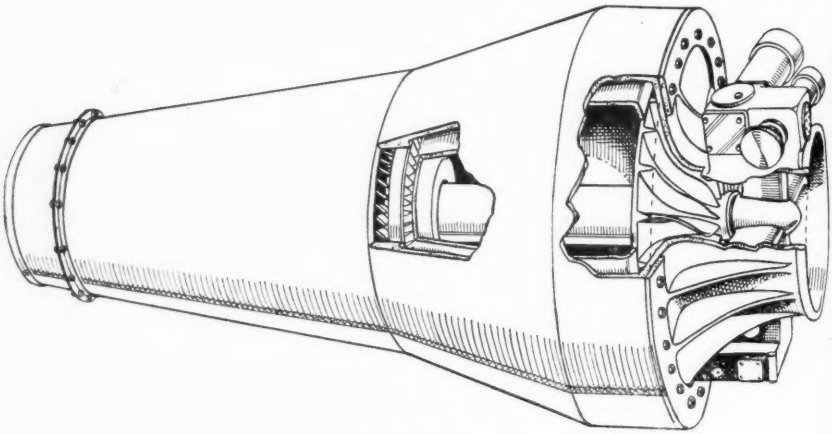


FIG. 95.

Diagram showing possible arrangement for complete turbine unit, with auxiliary drives ahead of compressor.

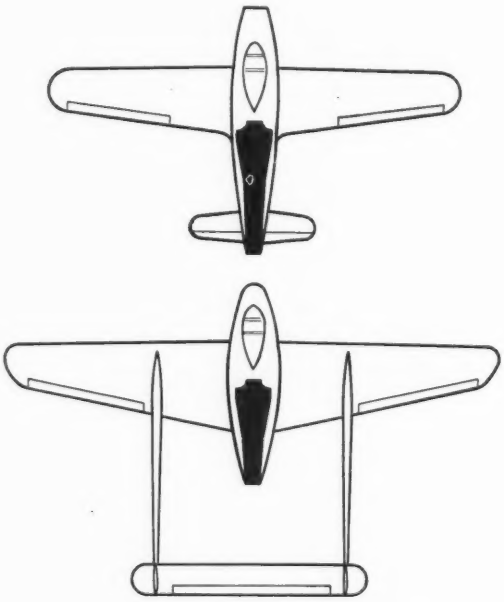


FIG. 96.

Outline diagram of two alternative types of small aircraft with jet-propulsion installation.

purposes, the remainder being added at a suitable position before the turbine, in order to cool the products of combustion, and allow the whole mass of gas to be reduced to a temperature which is acceptable to the turbine blades. After passing through the turbine D, the gas is discharged along the conduit E, and through the nozzle F, to atmosphere. All the power developed by the turbine wheel is

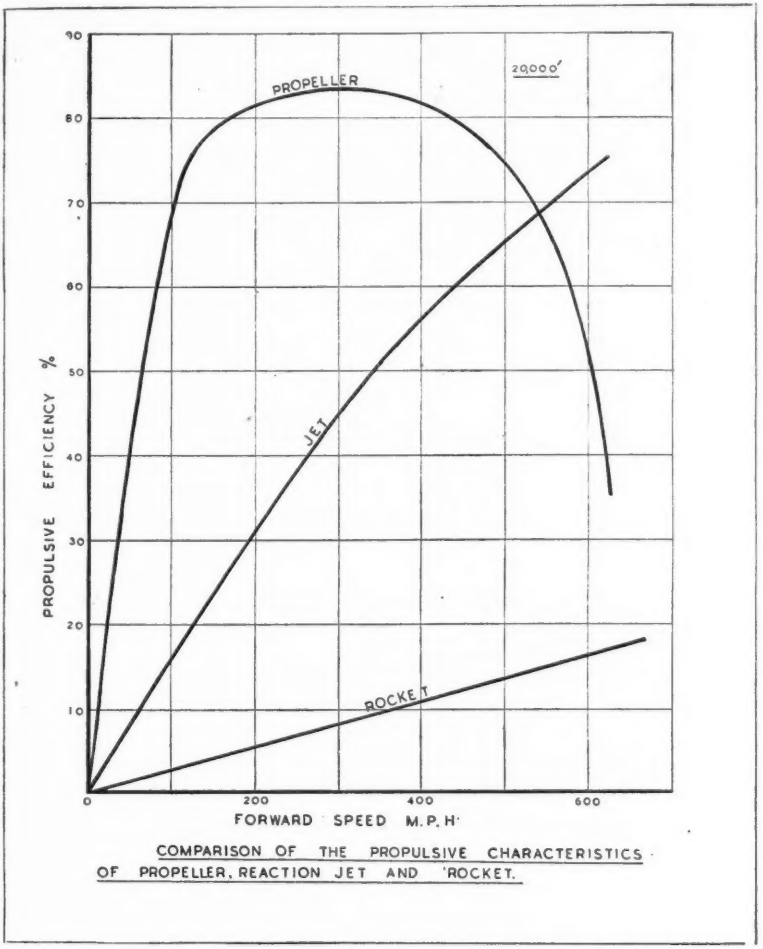


FIG. 97.

Curves showing propulsive efficiency for propeller, jet and rocket against speed at 20,000 feet.

absorbed in the compressor, and the aircraft is propelled solely by means of the thrust due to the change of momentum of the mass of air handled by the unit. The unit is started by means of an electric motor which runs the impellor up to a sufficient speed to supply air to the combustion chamber, and fuel is injected and ignited by means of the ignition plug C. As soon as combustion has commenced, the plug is cut out.

Fig. 94 shows a scheme drawing taken from one of the original Whittle patent specifications, indicating the use of an axial flow compressor in conjunction with a centrifugal type as shown in the previous figure. To Group Captain Whittle must be given the full credit of appreciating the capabilities of such a machine for handling sufficiently large mass flows of air to allow its practical application as a jet-propulsion unit.

Fig. 95 shows one possible arrangement for a complete jet-propulsion turbine unit including auxiliary drives ahead of the compressor, and Fig. 96 illustrates two alternative types of small high-speed machine indicating the manner in which such units could be installed.

The propulsive characteristics of the turbine and jet combination are quite different from those of the piston engine with propeller, and Fig. 97 shows the curves of propulsive efficiency plotted against speed at 20,000 ft. for propeller, jet and rocket. It will be seen, according to these estimates, that the jet shows no advantage in efficiency at this altitude below speeds of 550 m.p.h. The equivalent cross-over point at 30,000 ft. is of the order of 450 m.p.h.

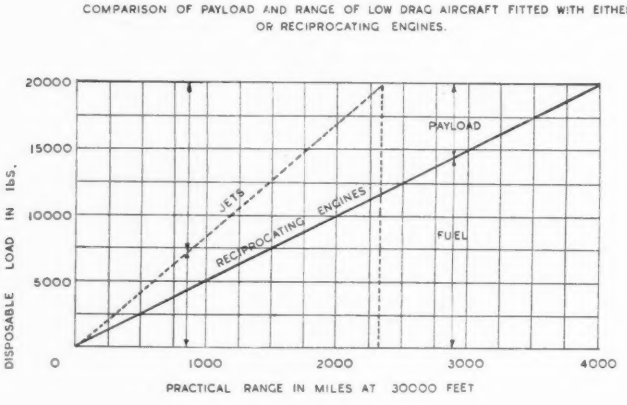


FIG. 98.

Diagram showing estimated comparison of payload and range for jet and reciprocating engine driven aircraft.

It is difficult to make a direct comparison between the fuel consumption of the gas turbine and pure jet-propulsion unit, and that of the conventional piston engine with propeller, as the consumption of the former is usually referred to in lb. fuel Thrust H.P./Hour, but, broadly speaking, at cruising conditions it is of the order of two to three times as great at the speeds and altitudes which are considered normal practice with the reciprocating engine.

For high-speed, high-altitude flying in machines with endurances up to three hours and ranges of about 1,500 miles, the pure jet turbine power plant will compete with the reciprocating engine and propeller, and this is ideally suited for use in fighter, fast medium bomber and special purpose civil aircraft.

Fig. 76 showed a possible layout for a high-speed civil machine suitable for carrying mail or other urgent commodities. This aircraft could be used for ranges up to 1,000 miles, carrying some 4,000 lb. pay-load, with a cruising speed of 420 m.p.h. at 30,000 ft. Figs. 98 and 99 show estimated comparisons on range and consumption bases between such a machine fitted with jet units and the same type with piston engines and propellers.

The outstanding features of the simple turbine and jet combination are its extremely low specific weight, its comparative simplicity in design, external cleanness, and low drag due to the elimination of slipstream effects. There seems to be no reason why the installed weight of the power unit should not be less than half that for an equivalent piston engine plant, and this is an important factor to be balanced against the high fuel consumption. The power plant should also be smooth running, free from mechanical clatter or intermittent exhaust noise, and moreover should be able to operate on kerosene or some other high flash-point fuel, thus minimising fire risk and troubles with vapour locking in the fuel supply lines at altitude.

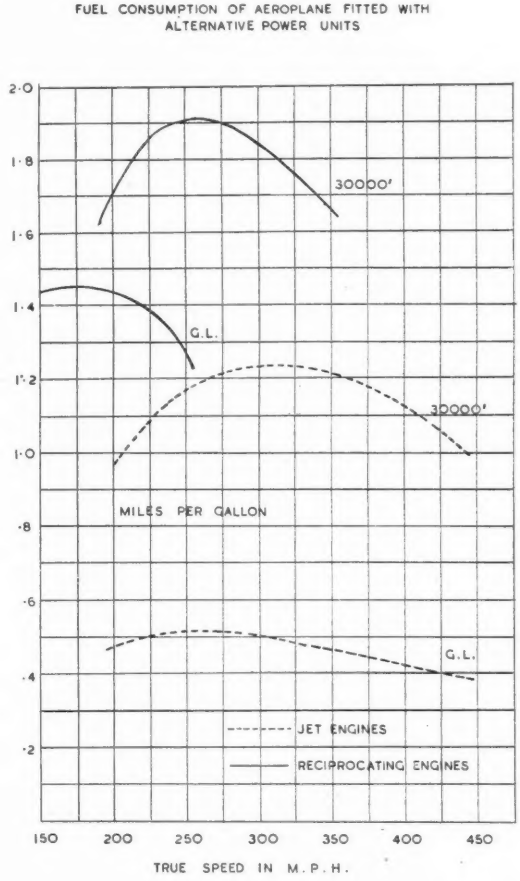


FIG. 99.

Curves showing estimated comparison of fuel consumption of jet machine and propeller type.

With regard to mechanical design, Figs. 93 and 94, which were referred to earlier, indicated that the main components of a jet-propulsion unit are the compressor, combustion chamber, turbine and jet pipe, with, of course, the necessary ancillary equipment such as fuel pump, generators, etc.

As indicated, the compressor may be of the centrifugal or axial type, depending upon the particular requirements of the design. Reference to the fundamentals of the constant pressure thermodynamic cycle suggests the necessity of using fairly high pressure ratios, and high turbine inlet temperatures, if reasonable thermal efficiency is to be achieved. There is theoretically an optimum value of compression ratio for use with any particular turbine inlet temperature. Since the jet discharge velocity influences the propulsive efficiency, the jet discharge passage and orifice must be carefully designed to match the operating characteristics of the turbine and compressor.

So much is known about the efficiency and performance of the centrifugal compressor, since this design has been developed to such an advanced stage for supercharging the piston engine, that every advantage has probably been taken of such background in the design of compressors for use in conjunction with the simple gas turbine and jet unit. In addition, the manufacture of the centrifugal compressor impellor is relatively simple, and there is still scope for improvement in efficiency and the use of higher pressure ratios with such machines.

However, with an advance in development and technique on axial flow compressors there is good reason to anticipate that they will eventually supplant the centrifugal type for all purposes, and it is proposed to refer to them later in more detail under the heading of power turbines driving propellers. Fig. 100 shows a single-stage turbine and jet-propulsion unit employing an axial flow compressor.

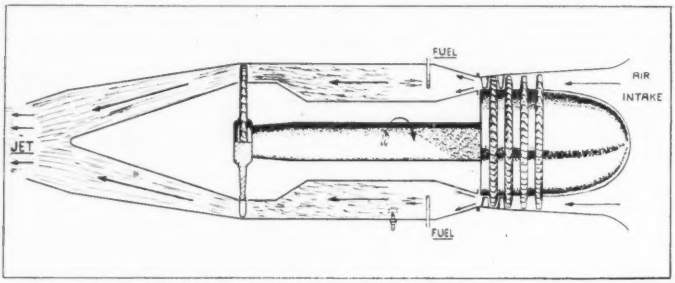


FIG. 100.

Outline diagram of single-stage turbine and jet unit with axial flow compressor.

With any form of compressor working at high pressure ratios and handling large volumes of air, there are many problems concerned with the choice of correct operating point, the avoidance of surge, and the necessity for reducing shock losses in regions of high-speed airflow.

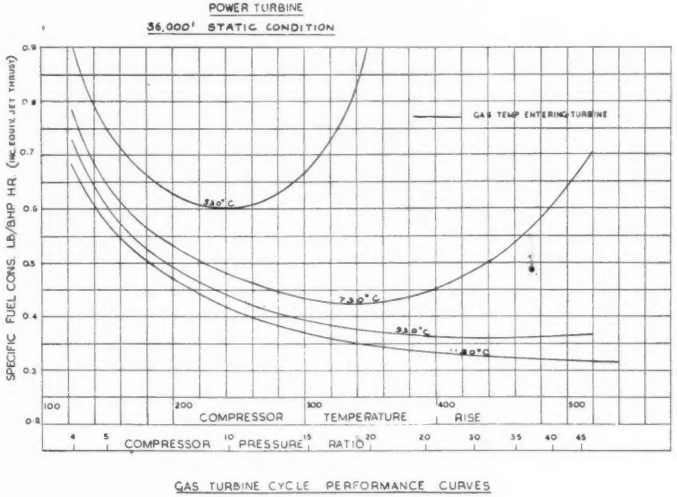
Another major problem on the gas turbine is that of ensuring satisfactory combustion at the enormous rates of heat input and high intensities required, and in addition there are the difficulties of maintaining combustion chamber walls at acceptable temperatures, of providing a reasonable degree of mechanical flexibility without flimsiness, and of obtaining the correct amount of turbulence to ensure proper mixing of the fuel.

However, we know that all these problems have in certain measure been overcome to such an extent as to allow the practical realisation of jet-propelled aircraft. The importance of this achievement cannot be over-estimated, and though attention has been drawn to the limitations on the application of the jet method of propulsion as applied to commercial or medium performance aircraft, it is fair to state that these limitations are to a considerable extent bound up with our present state of development on the aerodynamics of the aircraft themselves. The future of the simple jet method of propulsion depends entirely upon whether the aircraft manu-

facturers can entirely re-orientate their ideas and produce much cleaner aeroplanes. The power plant manufacturer is virtually in a position where he can now produce engines which can give a greater maximum speed performance than can actually be utilised.

There is no doubt that the experience gained on this new prime mover in its relatively simple form will be invaluable when we come to investigate the introduction of its more advanced derivatives in a wider field. This brings us to consider (*b*) the gas turbine driving a propeller.

The cycle and principles of operation of such a power unit are exactly the same as those outlined under the previous heading, except that the products of combustion are made to do more work in the turbine, which then supplies not only the power to drive the compressor, but also that required to drive a propeller. After the gases have been expended through the power turbine, any residual energy is absorbed in the form of thrust from suitable jet or jets. The division of power between the propeller and jet will depend to a certain extent upon the function of the particular machine, but, broadly speaking, may be of the order of 70 to 80 per cent. propeller and 30 to 20 per cent. jet thrust.



GAS TURBINE CYCLE PERFORMANCE CURVES

FIG. 101.

Curves indicating effect of working temperatures and compression ratio on efficiency.

Detailed analysis of the performance of gas turbines for ship propulsion and land installations have been presented in the technical press, and in the same way performance figures can be arrived at for aircraft units. It is not proposed to go into these in detail in this paper. Fig. 101 shows a family of curves which, based on certain initial assumptions, indicate the effect of working temperatures and compression ratios on the efficiency of the power unit. From these curves it can be seen that the ultimate efficiencies achieved with very high compression ratios and temperatures are comparable with those obtainable with the piston engine, but it is hardly necessary for me to point out that there are many obstacles in the path of the gas turbine designer and development engineer which will have to be overcome before such a goal as .32—.35 lb./B.H.P./Hr. fuel consumption can be reached. However, bearing in mind some of the evidence given previously in this paper, indicating the great progress which has been made with the piston

engine over the last ten to fifteen years, we cannot afford to look askance at these figures.

It is difficult at this stage to predict the exact forms which the layouts of gas turbines in large aeroplanes may take, but Fig. 102 shows a general arrangement for a complete unit driving contra-rotating pusher propellers and with jets discharging over the trailing edge of the wing outside the propeller disc. There appears to be a possible objection to an arrangement allowing the jets to discharge through the airscrew disc, as the velocity of the jets might be considerably higher than the velocity of flight while temperatures might be up to 500°C., and the action of the propeller blades entering and leaving the zones of high velocity and low density air might set up serious vibration in the blades and interfere with the airflow over them. It may be unfortunate if this is borne out by experiment, as it would be desirable with such an installation as that depicted to pitch the duct exits as close as possible in order to keep the radius of the bends relatively large to avoid losses. This whole question of ducting the large masses of gas away from the turbine, and arranging for their discharge in such a way that the maximum amount of thrust is obtained, with minimum duct losses, turbine back pressure

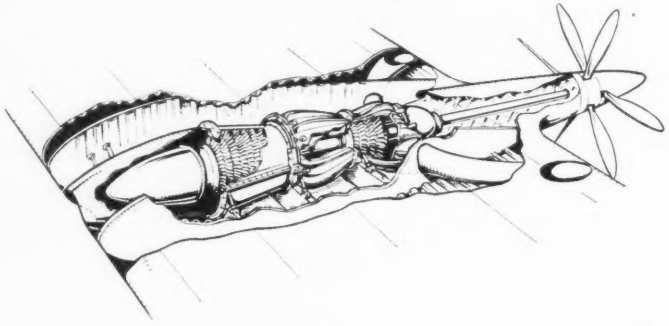


FIG. 102.

Diagrammatic sketch of wing section showing gas turbine installed and driving contra-propellers.

and slipstream interference, is at present largely a matter for conjecture. If we consider the turbine and compressor primarily, and design for the optimum aerodynamic forms of intake and exhaust, we are confronted with the possibilities of having to adopt complicated systems of shaft drives and bevel gears. If we aim for simplicity of the mechanical drives, then it appears difficult to arrange for low-loss ducting. There is no doubt, however, that a satisfactory solution will be arrived at. It is certain that we must take every advantage of the compactness of the gas turbine and suppress the power plant completely within the envelope of the wing, and in conjunction with laminar flow wings use pusher propellers perhaps of the contra-rotating type with six or more blades, or possibly at a later stage we can successfully apply some form of ducted propeller. It may be practicable to arrange for suitable control of the boundary layer by careful disposition of intake ducts and jet discharge nozzles. Figs. 103 and 104 show two projected civil machines of about 200,000 lb. all-up weight, using four gas turbine units, totalling some 20,000 h.p. Such a machine fitted with pressure cabins should be capable of cruising at 300 m.p.h. at 25,000/30,000 ft. over ranges from 2,000 to 3,000 miles.

Returning again to the gas turbine unit itself, it will be appreciated from the curves shown in Fig. 101 that it will pay to use high pressure ratios, and for this

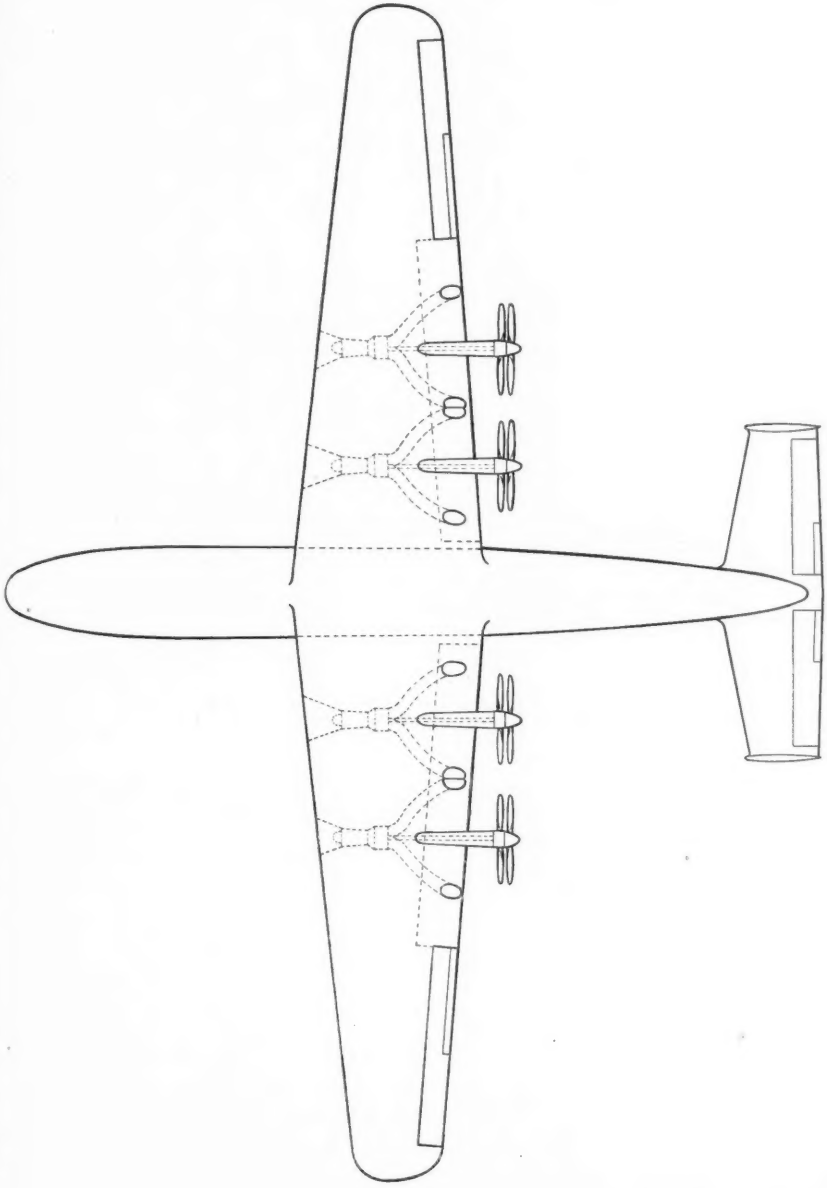


FIG 103.

Diagram of conventional 200,000 lb. aircraft with turbine installed driving propellers.

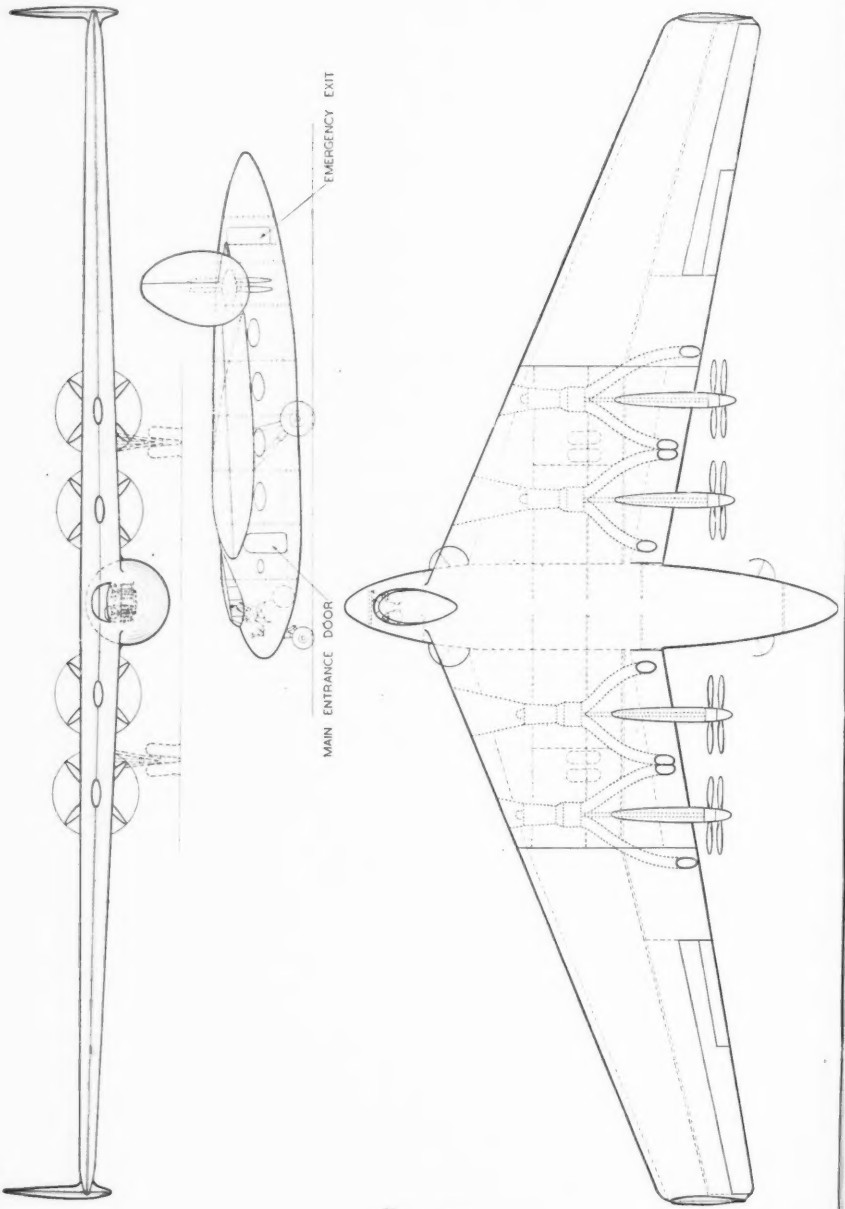


FIG. 104.

Diagram of tailless 200,000 lb. aircraft with turbine installed driving propellers.

reason the adoption of the axial flow compressor will be essential in the interests of power plant weight and good efficiency.

As mentioned in the introduction to this section, a considerable amount of experience has been accumulated on industrial types of gas turbines manufactured by the Brown Boveri and Escher Wyss Companies in Switzerland. They have carried out much pioneer research on the aerodynamic theory of aerofoils in cascade, both in the interests of steam and gas turbines. It is probably true to say that the steam turbine will derive considerable benefit from the further study of blade forms and compressor and turbine performance which must be intensively pursued if the compressors and turbines for internal combustion machinery are to be developed to the state of operating efficiency required for reasonable fuel economy.

Fig. 105 shows a 10-stage axial flow compressor for use in conjunction with a multi-stage axial flow power turbine such as that depicted in the general arrangement previously referred to.

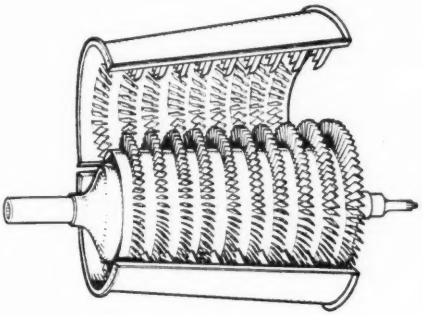


FIG. 105.

Diagrammatic sketch of 10-stage axial flow compressor opened up.

The specific weight of a propeller turbine combination would appear to vary with the pressure ratio, and quite high pressure ratios could presumably be achieved before the specific weight reaches that of the piston engine. The mechanical design of the turbine and compressor is relatively simple, and the stresses are more easily determined than in the case of the reciprocating engine. The major unknowns likely to cause trouble on the mechanical side are thermal distortion and blade vibration, which latter may be a serious problem as the size of machines and length of blades increase. Also there will certainly be special problems in connection with shaft sealing glands at the high pressure ends of compressors and turbines.

As far as the operation of axial flow compressors is concerned, there is still much to be learned. This type of machine tends to give rather peaky efficiency curves, and it will be one of the most important tasks of the gas turbine designers to increase the efficient operating range and thus ensure an adequate degree of flexibility with capacity for dealing with reasonable variations of mass flow without the danger of stage stalling or surge. Pressure ratios of 8:1, 12:1, and even higher, will have to be obtained in the course of development. I have always felt that it pays to allow a fair margin in capacity on the performance of any machine, be it aero engine or supercharger, and this will probably apply also to the gas turbine. If we design too small and have to work the compressor too near the limit of its capacity, a good deal of trouble with instability under certain conditions may be expected.

Some work has been carried out by Brown Boveri on axial flow compressors with variable pitch blades, but though such an arrangement would be ideal from the point of view of flexible operation over a wide range of mass flow, it is a difficult mechanical problem to consider variable pitch operation on units such as will be used for aircraft installations, particularly when one realises that stator vane angles and clearances would be completely upset by any change in pitch of the rotor vanes. Although we cannot neglect the possibilities of using multi-stage centrifugal compressors, it would appear that this type becomes somewhat heavy as the required pressure ratio increases, and it is unlikely that it will compete with the axial flow machine in view of the high efficiencies and other advantages which it is hoped to obtain with development on this type.

It is unfortunate that the displacement type of compressor has proved in the past, with the exception of the Lysholm machine, to be so inefficient and also to be so inherently bulky and heavy, as such a compressor would allow part throttle running of the gas turbine unit, and would facilitate operation over a wide range of mass flows, with maintained combustion chamber pressures and temperatures, and consequently high thermal efficiencies at part load conditions.

The theoretical advantages of employing heat exchangers, compressor intercoolers and reheat stages in the power turbine have been fully discussed in the technical press in connection with ship or land installations, but it is obvious that such equipment adds considerably to the complexity and weight of the system, although there is no question that we shall be hard put to it to approach the figures of thermal efficiency and fuel economy which we can quite fairly expect to obtain from future piston engines with turbo blowers and using further improved fuels.

The necessity of using a heat exchanger will naturally be governed to a certain extent by the speed at which the aircraft concerned are required to operate, since the primary function of such a device is usefully to absorb the heat energy of the gases leaving the power turbine, and to preheat the compressed air prior to its entry to the combustion chamber. Thus the greater the degree of heat exchange, better termed regeneration, the less energy will remain for disposal in the form of jet thrust.

In considering this whole problem of regeneration, apart from the increased weight of the system, we also have to take into account the duct losses and pressure drop incurred in diverting the large masses of compressed air and exhaust gas through the heat exchanger. The value of the total heat lost in this way, if large, will seriously affect the overall efficiency of the cycle, and therefore quite large degrees of regeneration may only result in quite small improvements in overall efficiency.

There is a limit to the accuracy with which it is possible to establish parameters indicating the pros and cons of cycle versus installation efficiency as a whole, and we must face up to the necessity of trying the various schemes in the flesh, and be prepared for some disappointments in order to arrive at the best results.

The effects of increases in blade operating temperature will undoubtedly offer every advantage in the case of the turbine propeller combination, and we shall look to the metallurgists to provide greatly improved materials with higher creep strength at elevated temperatures and greater resistance to erosion and corrosion. A serious factor to be considered in conjunction with such materials is the difficulty of working them, and there will be many forging and machining problems to be overcome. There will also be the question of establishing the most suitable combinations of different metals in compressor and turbine rotors and casings allowing for the correct degree of differential expansion to maintain the right blade clearances over the large range of temperatures which will be experienced.

The running time between overhaul for the gas turbine unit will probably be largely governed by the necessity for cleaning combustion chambers, periodic examination of blade fixings, and main bearing wear. The question of lubrication of the units will certainly be very much simpler than in the case of the piston

engine, and although some degree of oil cooling may be required, the heat to oil figures should be negligible compared with those encountered on our present high-power aero engines.

Earlier in this paper mention was made of the difficulties likely to be encountered with propeller vibration on the larger sizes of piston engine. One of the most important features of the turbine is the provision of a perfectly smooth torque characteristic, and the propeller manufacturer will welcome any relief which can be obtained on the problem of providing complete reliability, coupled with highest possible efficiency, on the large sizes of propellers, which may have to be used on some of our airliners of the future.

Another outstanding feature of the gas turbine is the fact that the technique of its design and development promises to allow a state of affairs whereby the aircraft manufacturer can have his power units " tailor made "—in other words, the design, development and manufacture of the aeroplane prototype and turbine engines to suit—can be effected simultaneously. This, as we know, has not been possible with reciprocating engines up to the present time, and the aircraft designer has in the past been faced with the alternative of taking a chance with new types of partially developed engines or fitting proven marks which set a limitation on the performance and design of the machine.

It is submitted that the time has now arrived when airframe designers should appreciate the significance of the golden opportunity which is almost within their grasp, to advance towards that ideal state in aircraft design, which can only come with the perfect matching of the power plant and airframe.

Although the preceding notes give only a glimpse of some of the aspects of these new and vital developments on the pure rotary internal combustion prime mover, and although the engineering world has as yet but scratched the surface of things to come, there is no question that we have already embarked upon a new era in the history of the prime mover and particularly with regard to its application for the propulsion of aircraft.

Under the three headings given earlier, reference was made to (*c*), the power unit consisting of a combination of compressor reciprocating engine and power turbine. The main object of considering such a scheme is to obtain the highest possible thermal efficiency by using the reciprocating engine as the combustion chamber, allowing higher maximum cycle temperatures than those obtainable with simple combustion chamber directly connected to the turbine. It is difficult, however, to visualise such a system approaching the specific weight of the straight turbine unit, and thus the fuel economy would only show to advantage in aircraft for use over very long ranges, say, of the order of 3,000-4,000 miles. In addition the combination of reciprocating engine and turbine involves the mechanical problems of both types of machine, and if full advantage of the system is to be taken, there may have to be a somewhat complex system of controls. It must also be appreciated that whereas the development of successful gas turbine units promises to be a fairly rapid process, once the fundamental features can be established and advantage can be taken of the scale effect, the development of a high-duty reciprocating engine, even in simple form, is a long job, and will control the time taken taken for successful realisation of the whole project in its combined form.

It is considered, therefore, that although such schemes must be fully investigated on their merits, we should not under any circumstances divert our efforts from the satisfactory realisation of the pure rotary machine, operating with sufficient flexibility and low enough fuel consumption, which will allow this attractive form of prime mover to compete with the piston engine in all but the low-power aero engine fields. If this goal can be achieved and there is no reason why it should not if sufficient effort and drive is forthcoming, then we can expect to see altogether new standards of power plant reliability and aircraft performance in a way that might never be possible with the piston engine, even in its most refined forms.

SECTION 12.—CONCLUSIONS.

From what I have said it will be gleaned that, with a few exceptions, notably the very early development before, and for a period after, the last war, this country has every reason to feel satisfied that it has taken a foremost place in the evolution of prime movers for aircraft for the last thirty years, and that when this war ends, we shall possess a family of high-powered aero engines which is second to none in regard to power at altitude and the maximum utilisation of a given lb. of material.

It is submitted that what we have got to do for the future is to face up to a carefully planned scheme which will ensure enthusiasm, keenness and co-ordinated team work from the whole country, both in regard to the improvement of materials for aircraft power plant and the actual development of the power plants themselves; further, that we must make sure that there will be no lull whatsoever or slipping back after this war, and that we shall have a concerted and adequate development programme covering the whole field and extending for at least ten years, which is the only way to obtain results on such a broad and complex problem.

I started this paper by saying that at the dawn of aviation, aircraft pioneers had been waiting on the evolution of a satisfactory and light enough power plant, which statement in broad principle holds good to-day, insomuch that if we are going to see the improvement in cleanliness and streamlining of aircraft which we believe is possible, and the step-up in speeds which we think has still to come, then the engine designer and power plant engineer must continue to produce better and more efficient complete power plant units.

The position, however, is somewhat reversed as regards the initiative, as compared with what has been the case in the past. With the prospect of the gas turbine being built in within the envelope of the wing, and the stimulus that this will give to improved and ducted conventional piston power plant, the responsibility and initiative are in fact, I submit, in the hands of the aircraft designer, and it will be necessary for him to produce airframes of considerably reduced drag and cleanliness, and incorporating new and improved technique, in order to justify and pay adequate dividends on the new power plants we believe are round the corner.

There is no need, however, for us to fall out as to where the responsibility lies, and this suggestion is simply thrown out as a spur and reminder to the aircraft designer of what is expected from him in the future. The engine fraternity appreciate that there is much for them to do in the ten years after the war, and that aircraft power plants have arrived at an intriguing and inspiring position, and providing we can have the right leadership, the future generation of young engineers in this country, who will have the privilege of working on this highly interesting branch of engineering, should have great opportunities. As I have endeavoured to bring out, aero engine development is one of the most difficult and most precise forms of engineering, but the designer and engineer who work on it have a unique opportunity to give vent to their initiative and imagination, and the very nature of the work enables them to use materials and methods which are prohibitive in any other branch of internal combustion engineering.

It is desired to emphasise that this country has pioneered the world in the development of the gas turbine for aircraft purposes up to the present time, and it is important that we should ensure that there is no chance of our losing the lead in this respect. Some people are most concerned that we are in danger of doing so, and it is sincerely hoped that those in authority will see to it that the outstanding pioneer work that has been accomplished in this country to date is not lost while others benefit and bring this initiative and imagination of our technical brains to practical fruition, while our own effort falls away. Such was the case, notably with the variable pitch propeller and the retractable undercarriage, both of which were originated and tested out in this country in practical

form for some years, but for which there was not enough vision and drive put behind their development to bring them to rapid realisation for everyday use.

At the same time, it is equally important that we should keep our balance and sense of proportion in regard to gas turbine development, and whereas the possibilities of this prime mover are undoubtedly very great indeed, and in years to come will replace the conventional engine in a number of different types of aircraft, the piston engine is by no means finished, and, at any rate for long-range aircraft, will hold the field, in my opinion, for at least another ten years, unless some quite unforeseen development occurs. It is for this reason that we must ensure high priority on the development of a logical new family of powerful, reliable and accessible piston engines, planned on a basis to make use of new developments and improved materials, to the best possible advantage, designed in a realistic way, and built as complete power plants.

In conclusion I would like to thank my colleagues and friends for the guidance they have given me in regard to this paper, the Armstrong Siddeley, Bristol, de Havilland, Napier and Rolls Royce Companies, and " The Aeroplane " and " Flight," who have been good enough to provide me with photographs and data.

Sir Oliver Simmonds, F.R.Ae.S., Member of Council, proposed a vote of thanks to the lecturer.

This he thought was a unique Wilbur Wright Memorial Lecture because, not only have they Wilbur Wright here in spirit, but they had him represented by so many of his fellow countrymen, trained technical men, whose ability and energy they had seen here in England.

Sir Roy Fedden had said that he had his paper submitted to the Censor and passed. He thought that was not the whole truth. He understood that M.A.P. were very excited over it. Now that the Wilbur Wright Lecture had been delivered M.A.P. can be restored to its equilibrium and the invasion may now start.

Last year Dr. Warner gave a brilliant example of what a Wilbur Wright Lecture should be. This year Sir Roy has excelled himself, and has given them his views of the future of aero engines. There should be better collaboration with America, and he was sure they all hoped that Sir Roy in his present position would find it possible to establish a closer friendship and liaison. Sir Roy was a Past-President of the Society and they were all glad to hear that he is now the President elect.

Sir Roy had done outstanding service in warning the Government that Germany was arming in the middle 30's. He had done great work in the improvement of lubricants. He spoke of the future with great hope. He was surprised to hear of Sir Roy's remarks regarding an 8,000 h.p. I.C. engine in 1960. It helped them to know that they had by no means finished with the I.C. engine.

In passing he would like to pay tribute to Frank Whittle's great work. He hoped that many young men who are beginning will ponder over Sir Roy's words, and in concluding this very sincere vote of thanks he would like to say that the I.C. engine would have a very great effect on victory, and make victory sure.

Air Commodore F. R. Banks, F.R.Ae.S., Member of Council: After Sir Oliver Simmonds' able speech he found it was a difficult job to say very much, but he would like to say it was a memorable occasion, firstly because it was the Wilbur Wright Memorial Lecture, secondly because it was only the second lecture on aero engines, and thirdly because Sir Roy had such strong views. He had dealt with the historic side, gas turbines, petrol engines, radial-cooled engines and many other sides that night. He would also like to pay tribute to the work of Frank Whittle and agreed with what Sir Roy had said. Sir Roy had given them the sleeve valve engine. He did not think the turbine would supersede

the petrol engine altogether, though for some purposes it would transplant the petrol, but not all.

He took great pleasure in seconding a hearty vote of thanks to Sir Roy Fedden for his very excellent paper.

After the Lecture the Annual Council Dinner was held in the Library of the Society at 4, Hamilton Place, at which the following were present:—

Mr. E. J. N. Archbald, B.Sc., Grad.R.Ae.S. (Member of Council).
Air Commodore F. R. Banks, O.B.E., F.R.Ae.S., M.I.Aut.E., F.I.P., M.S.A.E. (Member of Council).
Air Vice Marshal D. C. T. Bennett, C.B.E., D.S.O., F.R.Ae.S. (A.O.C., Pathfinder Group).
The Rt. Hon. The Viscount Bennett.
Air Chief Marshal Sir F. Bowhill, G.B.E., K.C.B., C.M.G., D.S.O., F.R.G.S. (Chief of Air Transport Command, R.A.F.).
Rear-Admiral D. W. Boyd, C.B.E., D.F.C. (Fifth Sea Lord).
Mr. Griffith Brewer, Hon. F.R.Ae.S. (Past President, R.Ae.S.).
Mr. A. C. Brown, B.Sc., F.R.Ae.S. (Member of Council).
Mr. S. Camm, C.B.E., F.R.Ae.S. (Member of Council).
The Rt. Hon. Sir Stafford Cripps, K.C.B., M.P. (Minister of Aircraft Production).
Dr. H. Roxbee Cox, D.I.C., B.Sc., F.R.Ae.S. (Vice President, R.Ae.S.).
Sir Maurice Denny, Bt., C.B.E., D.F.C. (Chairman, Air Registration Board).
Mr. W. C. Devereux, F.R.Ae.S. (Member of Council).
Lt.-General James H. Doolittle, F.R.Ae.S. (Commanding General, 8th U.S.A.A.F.).
Air Chief Marshal Sir W. Sholto-Douglas, K.C.B., M.C., D.F.C. (Commanding Coastal Command, R.A.F.).
Mr. G. H. Dowty, F.RAe.S. (Member of Council).
Mr. A. G. Elliott, C.B.E., M.I.Aut.E., M.S.A.E., F.R.Ae.S. (Member of Council).
Mr. L. F. A. D'Erlanger.
Sir A. H. Roy Fedden, M.B.E., D.Sc., M.I.A.E., F.R.Ae.S. (Past President, R.Ae.S.).
Mr. A. Gouge, B.Sc., F.R.Ae.S. (PRESIDENT, R.Ae.S.).
Major F. B. Halford, M.S.A.E., F.R.Ae.S. (Member of Council).
Sir Frederick Handley Page, C.B.E., F.R.Ae.S. (Management Committee, S.B.A.C.).
Mr. W. P. Hildred, C.B., O.B.E., M.A. (Director-General of Civil Aviation).
Mr. J. E. Hodgson, Hon. F.R.Ae.S. (Honorary Librarian, R.Ae.S.).
Mr. A. Hukins, (E.N.V. Engineering Company).
Professor Sir Bennett Melvill Jones, A.F.C., F.R.Ae.S. (Chairman, Aeronautical Research Committee).
Major H. R. Kilner. (Chairman, S.B.A.C.).
The Rt. Hon. The Viscount Knollys. (Chairman, British Overseas Airways Corporation).
Captain A. G. Lamplugh, F.R.Ae.S. (Honorary Treasurer, R.Ae.S.).
Mr. B. Lockspeiser, M.A., F.C.S., F.R.Ae.S. (Director of Scientific Research).
Major R. H. Mayo, O.B.E., M.A., A.M.Inst.C.E., F.R.Ae.S. (Member of Council).
Mr. F. G. Miles, F.R.Ae.S. (Management Committee, S.B.A.C.).
Captain H. B. Miller. (U.S. Naval Attaché for Air).
Mr. J. D. North, F.R.Ae.S. (Management Committee, S.B.A.C.).
The Hon. Clive Pearson. (British Overseas Airways Corporation).
Mr. G. E. Petty, F.R.Ae.S. (Member of Council).
Mr. R. K. Pierson, C.B.E., B.Sc., A.M.Inst.C.E., F.R.Ae.S. (Member of Council).

Captain J. L. Pritchard, Hon. F.R.Ae.S. (Secretary, R.Ae.S.).
Mr. E. F. Relf, F.R.S., F.R.Ae.S. (Vice-President, R.Ae.S.).
Mr. A. E. Russell, B.Sc., F.R.Ae.S. (Member of Council).
Sir Francis Shelmerdine, O.B.E., C.I.E., F.R.Ae.S. (Member of Council).
Major B. W. Shilson, O.B.E., M.I.Mech.E., F.R.Ae.S. (Member of Council).
Mr. A. F. Sidgreaves, O.B.E., F.R.Ae.S. (Management Committee, S.B.A.C.).
Sir Oliver Simmonds, M.A., F.R.Ae.S., M.P. (Member of Council).
Air Marshal R. S. Sorley, C.B., D.S.C., O.B.E., D.F.C., A.F.R.Ae.S. (C.R.D., Ministry of Aircraft Production).
Mr. W. R. Verdon Smith. (Management Committee, S.B.A.C.).
Sir Frank Spriggs, Hon. F.R.Ae.S. (Management Committee, S.B.A.C.).
Mr. R. S. Stafford, A.F.R.Ae.S. (Member of Council).
Mr. J. A. Thomson. (Management Committee, S.B.A.C.).
Eng. Vice-Admiral Sir Frederick R. G. Turner, K.C.B., O.B.E. (Engineer in Chief of the Fleet).
Mr. C. C. Walker, A.M.Inst.C.E., F.R.Ae.S. (Member of Council).
Mr. H. E. Wimperis, C.B., C.B.E., M.I.E.E., E.Eng., F.R.Ae.S. (Past President, R.Ae.S.).
Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S. (Solicitor, R.Ae.S.).

THE STRESSING OF DEFLECTED PROPELLER BLADES.

By C. F. Hodson, A.F.R.Ae.S., F.M.S.A.E.

A method of guided successive approximation is given for evaluating net stresses in a flexible propeller blade after deflection relief. This guidance is given by a simple hypothesis relating net bending moment to relief moment. This method follows from experience gained in the use of the late P. A. Ralli's work, "The Equilibrium of Loaded Impeller Blades," published in Volume XXXV of this Journal, and originated in a desire to reduce the work involved in his more accurate method. Twisted blades of irregular alignment are covered. When combined with a method employing a series of residual bending moments errors in total tensile stress are reduced below 0.2 per cent. throughout the blade after the second approximation. Three methods are discussed and complete arithmetical examples given. Other methods are referred to briefly.

1. Introduction.

This note is intended to cover the more interesting items of progress made since 1930 by the Fairey Aviation Company, Limited, in methods for ascertaining the relief centrifugal bending moments due to bending deflection in twisted propeller blades. Ref. 1 describes the only reliable method known to the writer in use at the commencement of this period. The first substantial change was made in 1932, when the time required to obtain a solution was reduced from over a week to about half a day without any considerable sacrifice in accuracy. Owing to independent research and the usual circulation of junior staff the 1932 method is now fairly widely known under various names, but this note would be incomplete without its inclusion as it forms the basis of subsequent methods. The convergence by this method is not very rapid as it only halves the error at each successive approximation. An alternative method reducing the error to about one-tenth at each step is also given. The worked out example has been taken at random, and is not by any means the best advertisement which could have been produced. A 20in. slide rule has been used for this, but in general a 10in. rule is sufficiently accurate. From the experience gained in the alternative method it has been possible to improve a very rapid American method by cutting out successive approximations and arriving at a direct solution.

2. 1932 Method.

It is supposed that preliminary calculations assuming the blade to be rigid have been completed, and that the centrifugal force C and gross bending moment M_0 throughout the blade have been calculated, due allowance having been made for any inherent irregularities in the line passing through the C.G.s of the various sections all along the blade.

3.

The axis about which the blades are twisted to adjust the pitch, at right angles to the thrust axis, forms a convenient datum to which to refer these inherent offsets, z and y, z being taken as positive forward in the thrust direction and y positive in the direction opposite to the rotation of the propeller. Any increments of z and y due to strain are denoted by ζ and η respectively, where ζ and η are obtained from the second integral of the net bending moment about

the neutral axis resolved in the appropriate directions. Moments about the other axis of the section are usually neglected on account of the large moment of inertia in that direction. In the case of circular sections, a judicious choice of ϕ, the pitch angle of the neutral axis will suffice.

$$\zeta = \int_0^r \int_0^r (M/EI) \cos \phi \, dr.dr \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$\eta = \int_0^r \int_0^r (M/EI) \sin \phi \, dr.dr \quad . \quad . \quad . \quad . \quad . \quad (2)$$

All bending moments will be called positive in the same direction as the thrust and torque bending moments.

4.

The relief moment due to centrifugal force is given by

$$R = -(A \cos \phi + Br \sin \phi)$$

where

$$A = \int_{\text{tip}}^r C(d\zeta/dr)dr$$

and

$$B = \int_{\text{tip}}^r C(d/dr)\,(\eta/r)dr \quad \Bigg\} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

C is the total centrifugal tension and ϕ the pitch angle of the neutral axis of the section, all at radius r from the axis of rotation of the propeller.

The inherent centrifugal bending moments for the rigid blade were obtained by inserting z and y in place of ζ and η in equation (3).

5.

In order to find the net bending moment ζ and η must be known and vice versa. Ref. 1, which explains the derivation of the above equations, also gives a rigid mathematical solution of the problem; as, however, this is too laborious for industrial purposes a method of guided successive approximation is used. This is based on the hypothesis—justified by results—that *at any station the relief bending moment is proportional to the net bending moment at that station.* This is, of course, only an approximation as it supposes that all other stations are momentarily behaving in the same manner as the station under consideration, in the sense that each receives the same percentage of the gross relief bending moment.

Suppose M_o to be the bending moment in the rigid blade at radius r (see paragraph 2), and R_o to be the relief centrifugal bending moment arising from the deflections which would normally be due to the same bending moment M_o in an elastic blade (*c.f.* equations 1, 2 and 3, inserting M_o in place of M).

Suppose M_1 to be the first approximation to the net bending moment, and R_1 to be the proportionate relief moment such that

$$R_1 : R_o : : M_1 : M_o \text{ by hypothesis.}$$

then

$$R_1 = R_o \, . \, M_1/M_o$$

but

$$R_1 = M_1 - M_o \text{ (R is always a relief to M_o, } i.e., \ R_n = M_n - M_o)$$

hence

$$M_1 = M_o^2/(M_o - R_o) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

Similarly for subsequent approximations

$$R_n = R_{n-1}.M_n/M_{n-1} = M_n - M_o$$
$$\therefore M_n = (M_o.M_{n-1})/(M_{n-1} - R_{n-1}) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

6. Discussion of Example.

A worked out example is given in the Appendix, and illustrated by Figs. 1 and 2. It will be seen from Table A and Fig. 4 that at the second approximation the net bending moment at the root is about 5 per cent. in error on the low side whilst the bulk of the important part of the blade is within 2 per cent. This is sufficiently accurate to determine whether the stresses may be permitted. From Table B it will be seen that ζ_1 is within 1/64 in. of the final answer, throughout the blade. It will be noticed that although the root moments and deflections increase with successive approximations the tip deflection at first actually reduces.

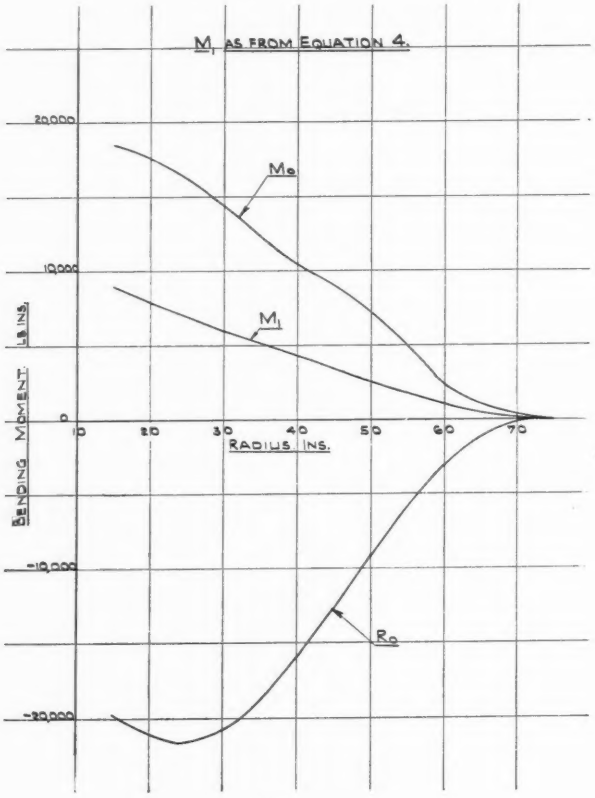


Fig. 1.

This method of 1932 appears to be very similar to that given in Ref. 2. The introduction of a constant scale factor in Ref. 2 illustrates the theory of the method, but serves no useful purpose in the arithmetic. With regard to the twisted blade, Ref. 2, leaves one under certain circumstances with the difficulty of choosing two moment curves which are correctly related throughout.

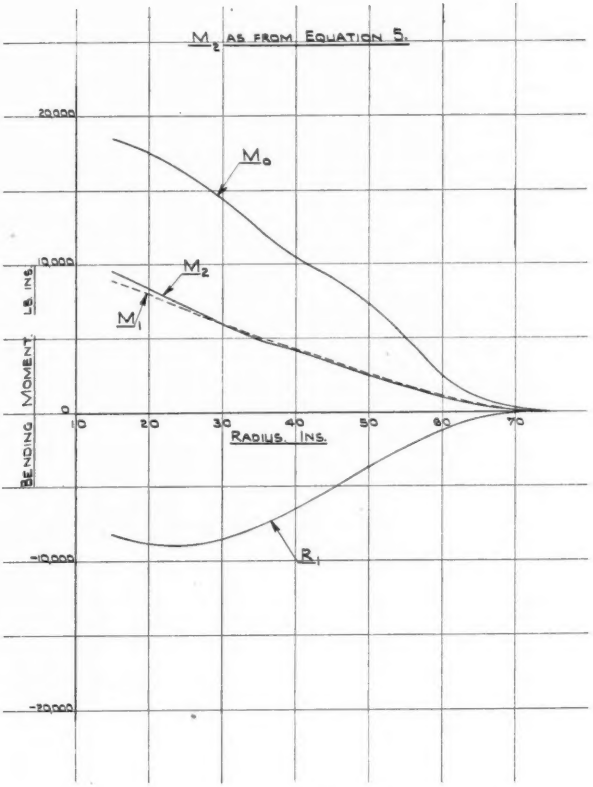


FIG. 2.

TABLE A.

SUCCESSIVE APPROXIMATE BENDING MOMENTS (LBS.-INCHES).

r (ins.)	M_0	M_1	M_2	M_3	M_4	Final M
15	18,400	8,867	9,530	9,800	9,990	10,095
18	17,990	8,349	8,820	9,075	9,200	9,270
24	16,450	7,099	7,260	7,340	7,390	7,431
30	14,490	5,940	5,920	5,920	5,930	5,906
36	11,969	4,725	4,620	4,555	4,520	4,463
42	9,860	3,945	3,880	3,861	3,861	3,831
48	7,059	2,820	2,750	2,737	2,740	2,720
54	4,590	1,894	1,882	1,886	1,896	1,879
60	2,394	1,028	1,039	1,050	1,060	1,050
66	861	408	427	436	440	438
72	94	57	64	66	67	67
75	0	0	0	0	0	0

TABLE B.

SUCCESSIVELY DERIVED DEFLECTIONS (INCHES).

r / 15	ζ_0	ζ_1	ζ_2	ζ_3	Final ζ
18	.0019	.0009	.0009	.0010	.0010
24	.0265	.0119	.0124	.0126	.0129
30	.0968	.0426	.0438	.0445	.0452
36	.2338	.1004	.1022	.1032	.1042
42	.4581	.1931	.1949	.1960	.1970
48	.7975	.3318	.3329	.3336	.3340
54	1.2859	.5310	.5308	.5301	.5299
60	1.9684	.8110	.8071	.8041	.8059
66	2.8907	1.1953	1.1870	1.1825	1.1905
72	4.0637	1.7033	1.6957	1.6928	1.7085
75	4.7234	1.9963	1.9931	1.9923	2.0121

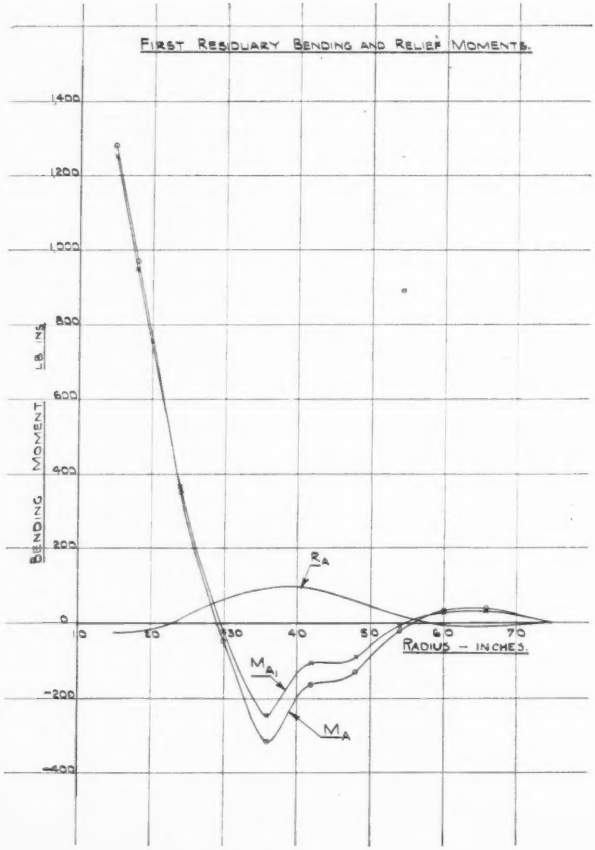


FIG. 3.

7. ALTERNATIVE METHOD.

In place of the second approximation given above, a more rapid convergence towards the final answer is given by an alternative method. Consider a blade having a gross bending moment equal to $M_1 - R_1$ instead of M_o. The complete problem for such a blade would then have been solved, and the deflected shape of the blade would be given by $f(z, y, \zeta_1, \eta_1)$. This blade only differs from the actual blade as regards its gross bending moment, the difference being $M_o - M_1 + R_1$. Call this difference M_A the first residual bending moment. This

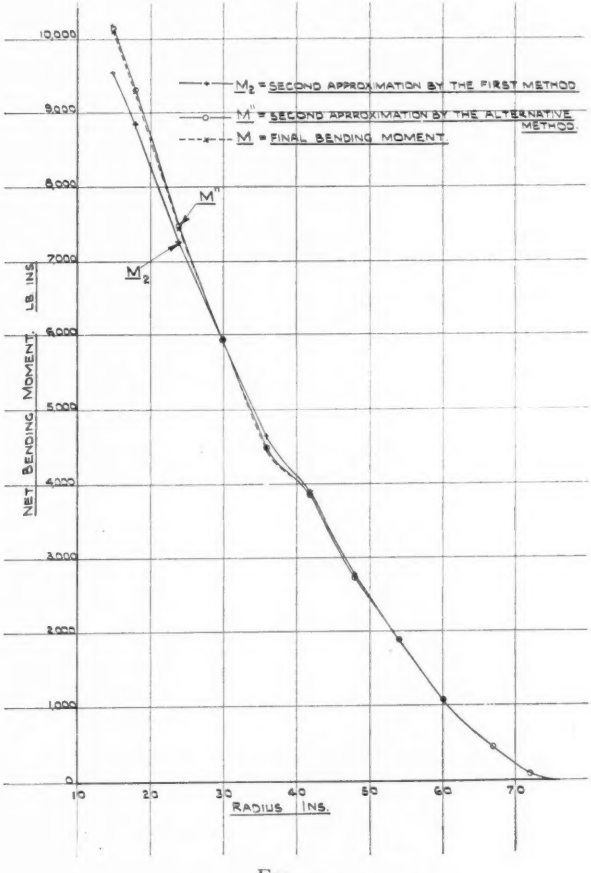


FIG. 4.

residual moment has not yet been suitably treated to find its appropriate deflection relief, but in the same way as the bending moment due to deflection can be treated separately from that due to inherent offsets, so this residual moment M_A can be treated by itself, using equations 1 to 4, but inserting M_A in place of M_o and M_{A1}, R_{A1}, ζ_A and η_A, respectively, in place of M_1, R_1, ζ_o and η_o. See Fig. 3.

Corresponding terms at the same radius are additive in any order. Thus the deflection is given by $\zeta_1 + \zeta_{A1}$ and $\eta_1 + \eta_{A1}$. The centrifugal force is not sensibly

affected by η or ζ, consequently the relief moments, hence the net moments, are also commutative. The second approximation to the net bending moment becomes

$$M^{11} = M_1 + M_{A1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

Fig. 4, and the relief moment equals $R_1 + R_{A1}$.

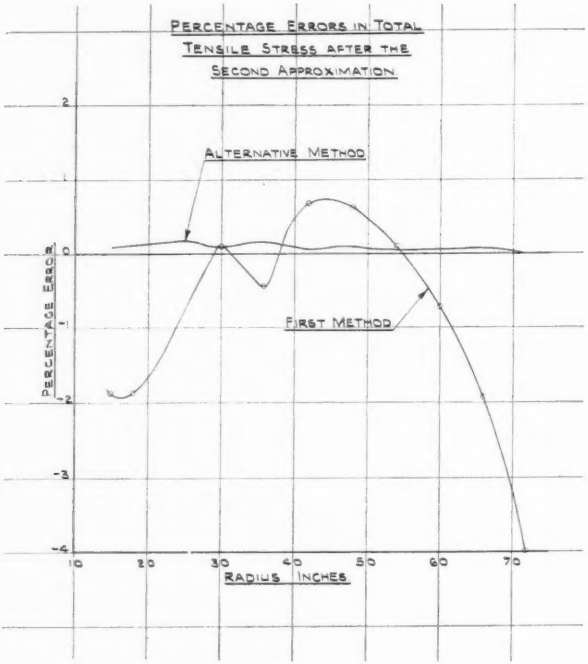


FIG. 5.

8. DISCUSSION OF EXAMPLE BY ALTERNATIVE METHOD.

It will be seen by comparing M^{11} in Table X of the appendix with Table A in the script that M^{11} is within 0.4 per cent. of the correct value at the root. Fig. 5 shows the percentage error in total stress at the root to be under 0.2 per cent. Both these errors reduce towards the tip.

If for any special purpose greater accuracy is desired a third approximation may be effected by operating in the same manner on M_B where

$$M_B = M_A - M_{A1} + R_{A1} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

leading to

$$M^{111} = M_1 + M_{A1} + M_{B1} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

9. COMPARISON OF THE TWO METHODS.

Although the first method does not give such a rapid convergence as the alternative method it has the advantage that each approximation is largely independent of the previous one, so that errors are only carried forward to a minor degree, each approximation forming a rough check on the previous work. The work of both methods could be halved if one were prepared to consider the blade as plane and untwisted. This is not recommended.

10. STANDARDISED BLADE FORMS.

If standardised blade shapes are used a further saving in work can be effected. Suppose that it is required to stress a blade having all its dimensions x times those of a standard blade which has already been stressed by the above method. Suppose also that the r.p.m. have been multiplied by z. Imagine for the time being the net moment M_1 at similar stations to be unchanged, then the deflection would be given by

$$\zeta = \int_0^{r_1} \int_0^{r_1} (M_1/Ex^4 I_1)\, x^2 . dr_1 . dr_1 = \zeta_1 / x^2 \quad . \quad . \quad . \quad (9)$$

and $\eta = \eta_1/x^2$, using the suffix 1 to indicate terms of the known blade.

$$C = x^3 m_1 z^2 w_1^2 x r_1 = x^4 z^2 C_1 .$$

The corresponding relief moment varies as $C.f(\eta, \zeta)$ and equals $x^2 z^2 R_1$.

The differentiation of ζ with respect to r and the subsequent integration of its product with C cancel out further powers of x, similarly for η/r with a further r outside the integral. See equation 3.

The gross moment for such an arrangement would be

$$M_1 - x^2 z^2 R_1 .$$

This rather arbitrary moment curve will probably differ from that for which a solution is now required except at the tip where the value is zero. If the ordinates of this curve are multiplied by a suitable constant K it can be made to agree at a further point, say, one-third of the radius from the centre.

The gross BM then becomes

$$K_1 (M_1 - x^2 z^2 R_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

This gross bending moment can be subtracted from the gross BM obtained from stressing the new rigid blade, and the difference treated as the first residue M_A. If blade twist is being neglected only Tables VIII and X are required to find M_{A1}, and these tables will be simplified by taking cos ϕ equal to unity and sin ϕ zero. The second approximate net BM is given by

$$M^{11} = M_{A1} + K_1 M_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

With certain types of shaping machines it is possible to form a longer blade, but not to alter the sectional and angular dimensions at corresponding proportionate radii. In this case x is only applied to the radius r. Expression (9) for the gross bending moment becomes

$$M_1 - x^4 z^2 R_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

This when made to intersect the actual gross bending moment curve becomes

$$K_1 (M_1 - x^4 z^2 R_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and $M^{11} = M_{A1} + K_1 M_1$ as before, giving the desired second approximate net bending moment.

The degree of accuracy is dependent upon the size and shape of the residuary bending moment curve, but should be within one per cent. $K_0 (M_0 - x^2 z^2 R_0)$ could be used in place of equation 10 if $M_1 + R_1$ are not available.

11. MODIFIED AMERICAN METHOD.

A very interesting method is given in Ref. 3. It is stated to be a method of successive approximation, but by means of the residuary moment method it leads to a conclusive answer, the accuracy of which depends upon various matters which will be discussed after a short explanation of this method has been given.

Fig. 6 illustrates a short length of the untwisted blade. It will be seen that the bending moment at the outer end of the element

$$M_2 = M_1 + \delta\zeta (C_2 + \delta C/2) + \delta r\, (S_2 + \delta S) \quad . \quad . \quad . \quad . \quad (14)$$

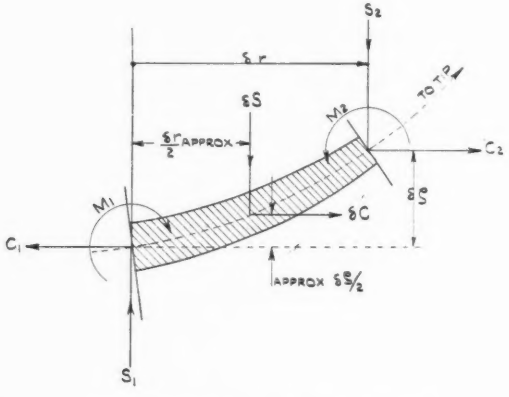
where $\delta\zeta = (d/dr)\zeta . dr$ over the finite element and $S = dM_0/dr$, then

$$M_2 = M_1 + \delta\zeta \text{ (mean } C) + \delta r \text{ (mean "shear")} \quad . \quad . \quad . \quad (15)$$

$\delta\zeta$ should of course be derived from the BM all along the element or the mean M/EI.

Any reasonable value of net BM is assumed at the root, and the corresponding BM at the other end of the element estimated from equation 15, and so on working across and across Table XI until the tip is reached. As it is most unlikely that a correct value for the root BM has been assumed, the BM at the tip will not be zero. Ref. 3 suggests a method of successive trials in order to find the correct root moment, and hence correct moments throughout.

It will be seen, however, from the first approximation, Table XI, that the gross moment throughout contains a constant error. A corrective residuary bending moment can be derived by assuming, say, 1,000 lb. ins. net root moment and no " shear " but identical centrifugal forces. This leads to an increasing net moment towards the tip and a constant gross moment along the blade, Table XII. This, when suitably scaled up or down, forms a correction to the previous gross moment. The corresponding net moments are then added together.



ELEMENT OF BLADE BETWEEN STATIONS.

FIG. 6.

Tables XI and XII in the Appendix give an example for the blade previously discussed. As the mean BM for the element is not known initially the deflection is based on the moment at the inner end of the element. The error arising from this arrangement is less than that which would follow from using the mean moment for deflections and assuming that the differences between adjoining net moments are equal to the differences between adjoining mean net moments.

Table XIII is a check back to the gross moment from the net moment derived by this third method. It shows errors of 1.46 per cent. at the root in spite of the conclusive arithmetical agreement at the tip. Comparing col. 10, Table XII, with the final M in Table A it will be seen that the error due to neglecting ϕ amounts to about 19 per cent. at the root.

Taking the untwisted blade and applying a twist to it, it will be seen that the relief moments obviously resolve differently with respect to the new directions of the neutral axes. Applying simply this resolution effect of ϕ to the integrals A and B of equation 3 the first step in differentiating this expression can be written as

$$-\frac{dR}{dr} = \frac{Ad}{dr}(\cos\phi) + Br\frac{d}{dr}(\sin\phi) + \cos\phi\frac{d}{dr}(A) + \sin\phi\frac{d}{dr}(Br).$$

A and B being integrals from the tip towards the root are not accurately obtainable when required. Hence this method can only be applied to the untwisted blade where $(d/dr)\cos\phi$ and $(d/dr)\sin\phi$ are zero causing their products with A and B to vanish.

12. Hinged Blades.

The initial treatment of hinged blades takes place in the "rigid" blade calculations. That is the equilibrium of the blade about its hinge due to varying centrifugal force, thrust and torque, ϕ, radius, and offsets y and z arising from motion about the hinge must first be established on the assumption that the remainder of the blade—apart from the hinge—is rigid.

A bending moment curve M_0 about neutral axes of the sections is then obtained as for ordinary rigid propeller blades. In this case a station is also taken at the hinge, with ϕ equal to the pitch angle of the hinge in end view of the blade. M_0 is of course zero at this point. Additional stations must be taken close to the hinge having ϕ relative to the neutral axis. M_0/EI at the hinge will be taken as zero regardless of the numerical value of I. R_1 is then found from M_0 by equations 1, 2, 3 and 4. This leaves a net moment equal to R_1 about the hinge which must be eliminated in the same manner as before for the rigid blade, in order to find a further position of the blade about the hinge which will reduce R_1 plus the original hinge moment to zero. The deflection stressing is then repeated with new values of M_0 and carried through to M_2. This process is repeated until M_1 is within 5 per cent. of M_2. In short, first the hinge is taken as free and the blade as rigid, then the hinge is locked in this position and the blade taken as flexible, only in turn to be frozen whilst the hinge is again freed.

The alternative method of residual moments may also be used, but only residuary moment curves derived from the same position of the blade about its hinge may be added, so long as the centrifugal force, and to a smaller extent ϕ, vary sensibly with rotation of the blade about the hinge.

13. Conclusions.

1. Errors in net bending moment of the order of 20 per cent. may arise from assuming the blade as untwisted, although doubtless if all moments are resolved into one special direction better results may be obtained.

2. Of the untwisted blade methods, the modified American method is the most rapid. Apart from the large error due to this over-riding assumption small ones arise from the distance apart of the stations and from the assumed mean moment on each section.

3. Of the twisted blade methods the alternative to the 1932 method gives the most accurate answer with a reasonable amount of work.

4. The 1932 method is sufficiently accurate for most purposes and easy to operate.

5. Untwisted blade methods are not recommended.

I am indebted to the Fairey Aviation Company, Limited, for permission to publish this note, and to my colleague, E. W. Roberts, for his kind collaboration. The opinions expressed are solely those of the author.

SYMBOLS.

C = total centrifugal force from tip to the station under consideration.
M_0 = the bending moment about the neutral axis as obtained from stressing a supposedly rigid blade.
$S = dM_0/dr$.
M_1 = the first approximation to the net bending moment.

R_0 = the relief bending moment due to the centrifugal force and the deflections η_0 and ζ_0.
R_1 = the relief bending moment due to the centrifugal force and the deflections η_1 and ζ_1.
z = co-ordinate of C.G. of section of blade in the thrust direction.
y = co-ordinate of C.G. of section of blade in the opposite direction to the rotation of the propeller.
ζ_0 = the increment of z due to M_0.
ζ_1 = the increment of z due to M_1.
η_0 = the increment of y due to M_0.
η_1 = the increment of y due to M_1.
E = Young's modulus of elasticity.
I = the moment of inertia of a section of the blade about the neutral axis.
K = scale constant for moment curves.
r = the radius at which the section is being considered.
D = diameter of propeller.
ϕ = the pitch angle of the neutral axis.
M^{II} = total net bending moment by the alternative method, comprising two terms M_1 and M_{A1}.
M^{III} = total net bending moment by the alternative method, comprising three terms M_1, M_{A1} and M_{B1}.

SUFFICES.

$_0$ indicates original value before approximation.
1, 2 and 3 show successive approximations.
A, B and C show successive residues in the alternative method.
A_1 = first approximation of the first residue.
M_{A1} = first approximation to the first net residuary bending moment.

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2. Stressing of Airscrew Blades. J. B. B. Owen, Aircraft Engineering, Vol. XII, 1940, April, p. 97.
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APPENDIX

TABLE I.

DATA.

r ins.	$\sin\phi$	$\cos\phi$	M_0 lb./ins.	C lbs.	E lbs./in.^{2}	I ins.^{4}
15	.6603	.7420	18,400	37,114	Mean E 1.55×10^6 Improved wood	32.18
18	.6295	.7769	17,990	33,018		16.45
24	.5474	.8370	16,450	27,822		6.51
30	.4698	.8828	14,490	23,426		4.53
36	.3934	.9193	11,969	18,809		3.02
42	.3267	.9451	9,860	14,243		1.88
48	.2709	.9626	7,059	9,992		1.08
54	.2247	.9745	4,500	6,308		.54
60	.1854	.9827	2,394	3,382		.226
66	.1519	.9884	861	1,331		.070
72	.1228	.9924	94	178		.0100
75			0	0		

The blade and hub are assumed to be rigid inboard of 15 inches radius.

TABLE II.

DEFLECTIONS ζ_o.

Col.	1	2	3	4	5	6	7
r	$(M_o/I)\cos\phi$	Mean $(M_o/I)\cos\phi$	Mean (M_o/I) $\cos\phi\ dr$	Σ_o^r	Mean Σ	$(d\zeta/dr)\ dr$	ζ_o
15	425			0			
		638	1.914		·957	.001853	
18	850			1.914			.0019
		1.492	8.892		6,360	.02462	
24	2.114			10,806			.0265
		2.469	14.814		18.213	.07052	
30	2,824			25,620			.0970
		3.233	19.398		35,319	.1368	
36	3.643			45,018			.2338
		4.300	25,800		57.918	.2243	
42	4,956			70,818			.4581
		5.624	33.744		87,690	.3394	
48	6.292			104,562			.7975
		7.288	43,728		126,426	·4884	
54	8.283			148,290			1.2859
		9,347	56.062		176,321	·6825	
60	10,410			204,351			1.9684
		11.285	67,710		238,207	.9223	
66	12,160			272,062			2.8907
		10,360	62,160		303,142	1.173	
72	8.559			334,222			4.0637
		4.279	12.837		340.641	.0597	
75	0			347.059			4.7234

Col. 6 = $dr \times E \times$ Col. 5. E has been inserted here. It is a function of r over the root portion of the blade, and could just as well have been introduced in Col. 1 if desired.

TABLE III.

DEFLECTIONS η_o.

Col.	1	2	3	4	5	6	7	8	9
r	(M_o/I) $\sin\phi$	Mean (M_o/I) $\sin\phi$	Mean (M_o/I) $\sin\phi\ dr$	Σ_o^r	Mean Σ	$(d\eta/dr)\ dr$	η_o	η_o/r	(d/dr) $(\eta_o/r)\ dr$
15	383			0					
		536	1.608		804	.00156			.000086
18	689			1,608			·00156	·0000864	
		1.036	6.216		4.716	.01826			.000740
24	1,383			7.824			.01982	.000826	
		1.443	8.658		12,153	.04704			.001403
30	1.503			16,482			.06686	.0022285	
		1.531	9.186		21.075	.08158			.001894
36	1.559			25,668			.14844	.004123	
		1.636	9,816		30,576	.1184			.002230
42	1,713			35.484			.26684	.006353	
		1.742	10.452		40.710	.1576			.002489
48	1.771			45 936			.42444	.008842	
		1.841	11.046		51.459	.1093			.002708
54	1,910			56,982			.6237	.011550	
		1,937	11.622		62,793	.2431			.002897
60	1.963			68,604			.8668	.014447	
		1.916	11,496		74,352	.2878			.003047
66	1.868			80,100			1.1546	.017494	
		1.464	8,784		84.492	.3271			.003086
72	1.059			88,884			1.4817	.02058	
		529	1.587		89.678	.3472			.003800
75	0			90.471			1.8289	.02438	

TABLE IV.

Relief B.M. R_0.

Col. r	1 Mean C	2 $C\,(d\zeta_0/dr)\,dr$	3 Σ^r_{tip}	4 $\cos\varphi\Sigma$	5 $C\,(d/dr)(\eta_0/r)\,dr$	6 Σ^r_{tip}	7 $r\sin\varphi\Sigma$	8 $-R_0$	9 M_0-R_0
15			23.731	17.630		214.45	2,154	19,784	38,184
	35.066	65			3.03				
18			23,666	18,390		211.42	2,396	20,786	38,776
	30.420	749			22.50				
24			22,917	19,180		188.92	2,483	21,663	38,113
	25.624	1.807			35.94				
30			21,110	18,640		152.98	2,157	20,797	35.287
	21.117	2.889			40.00				
36			18,221	16,750		112.98	1,602	18,352	30.321
	16.526	3.707			36.85				
42			14,514	13.720		76.13	1,044	14.764	24.624
	12,117	4.112			30.16				
48			10,402	10,010		45.97	598	10,608	17,667
	8,150	3,980			22.07				
54			6,422	6,258		23.90	291	6,549	11.139
	4,845	3,306			14.05				
60			3,116	3,062		9.85	110	3.172	5,566
	2.356	2.173			7.18				
66			943	932		2.67	27	959	1,820
	754	884			2.33				
72			59	59		.34	3	62	156
	.89	59			.34				
75			0					0	0

Col. 8, see equation 3.

TABLE V.

Deflections ζ_1.

Col. r	1 M_1	2 $(M_1/I)\cos\phi$	3 Mean $(M_1/I)\cos\phi$	4 $(M_1/I)\cos\phi\,dr$	5 Σ^r_0	6 Mean Σ	7 $(d\zeta_1/dr)\,dr$	8 ζ_1
15	8,867	205			0			0
			290.5	899		450	.00087	
18	8,349	394			899			.00087
			653.5	3.921		2.860	.01107	
24	7.099	913			4,820			.01194
			1.035	6.210		7.925	.03068	
30	5.940	1.157			11,030			.04262
			1,297	7.782		14.921	.05780	
36	4.725	1.437			18.812			.10042
			1.710	10,260		23.942	.09265	
42	3.945	1.984			29.072			.19307
			2.248	13,488		35,816	.1387	
48	2.820	2,512			42,560			.33177
			2,966	17,796		51.458	.1992	
54	1,894	3,420			60,356			.53097
			3,945	23,670		72.191	.2800	
60	1,028	4.47 >			84,026			.81097
			5,118	30,708		99.380	.3843	
66	408	5.765			114.734			1.19527
			5,469	32.814		131,141	.5080	
72	57	5,172			147.548			1.70327
			2,586	7.758		151.427	.293	
75	0	0			155.306			1.99627

Col. 1, see equation 4.

TABLE VI.

Deflections η_1.

Col.	1	2	3	4	5	6	7	8	9
r	(M_1/I) $\sin\phi$	Mean (M_1/I) $\sin\phi$	Mean (M_1/I) $\sin\phi\ dr$	$\Sigma \frac{r}{0}$	Mean Σ	$(d\eta_1/dr)\ dr$	η_1	η_1/r	(d/dr) $(\eta_1/r)\ dr$
15	184			0			0	0	
		251.5	755		377.5	.000731			.0000406
18	319			755			.000731	.0000406	
		458.0	2,748		2,129	.00824			.0003332
24	597			3,503			.00897	.0003738	
		606.5	3,639		5,323	.02062			.0006132
30	616			7,142			.02959	.0009870	
		615.5	3,693		8,989	.03480			.000802
36	615			10,835			.06439	.001789	
		650.5	3,903		12,787	.04950			.000923
42	686			14,738			.11389	.002712	
		696.0	4,176		16,826	.06520			.001020
48	706			18,914			.17909	.003732	
		747.0	4,482		21,155	.08105			.001101
54	788			23,396			.26104	.004833	
		815.5	4,893		25,843	.10010			.001187
60	843			28,289			.36114	.006020	
		864.0	5,184		30,881	.11950			.001260
66	885			33,473			.48064	.007280	
		762.5	4,575		35,760	.13850			.00132
72	640			38,048			61.914	.008600	
		320.0	960		38,528	.0746			.000646
75	0			39,008			6.0374	.000246	

TABLE VII.

Relief B.M. R_1.

Col.	1	2	3	4	5	6	7	8	9
r	$C\ (d\zeta_1/dr)\ dr$	$\Sigma \frac{r}{tip}$	$\cos\phi\Sigma$	$C\ (d/dr)$ $(\eta_1/r)\ dr$	$\Sigma \frac{r}{tip}$	$r \sin\phi\Sigma$	$-R_1$	M_1-R_1	M_2
15		9.890	7.345		90.56	909	8.254	17.121	9,530
	31			1.42					
18		9.859	7.660		89.14	1.010	8,670	17,019	8,820
	337			10.10					
24		9,522	7.960		79.04	1.039	8.999	16,098	7,260
	786			15.72					
30		8.736	7.710		63.32	893	8,602	14,542	5,920
	1.221			16.94					
36		7.515	6.905		46.38	657	7,562	12,287	4,620
	1,532			15.26					
42		5.983	5.655		31.12	427	6,082	10,027	3,880
	1,690			12.38					
48		4,293	4,130		18.74	244	4.374	7.194	2,750
	1,623			8.97					
54		2.670	2.600		9.77	119	2,719	4,613	1,882
	1,356			5.75					
60		1,314	1,291		4.02	45	1,336	2,364	1,039
	985			2.97					
66		409	404		1.05	10.5	415	823	427
	383			.99					
72		26	26		.06	.5	26	83	64
	26			.06					
75	0	0	0		0	0	0	0	0

Col. 7, see equation 3. Col. 9, see equation 5.

ALTERNATIVE METHOD.

TABLE VIII.

DEFLECTIONS ζ_A.

Col.	1	2	3	4	5	6	7	8
r	M_A	$(M_A/I)\cos\phi$	Mean $(M_A/I)\cos\phi$	$(M_A/I)\cos\phi\, dr$	Σ_o^r	Mean Σ	$(d^2\zeta_A/dr)\, dr$	ζ_A
15	1,279	29.50			0			
			37.68	113.06		56.6	.000110	
18	971	45.87			113.1			.000110
			45.57	273.42		249.8	.000966	
24	352	45.27			386.5			.001076
			17.57	105.42		439.2	.001699	
30	− 52	− 10.13			491.9			.002775
			− 53.44	−320.64		331.6	.001283	
36	−318	− 96.75			171.3			.004058
			− 90.38	−542.25		− 99.8	−.000387	
42	−167	− 84.00			− 371.0			.003671
			−102.15	−612.90		− 677.5	−.002623	
48	− 135	−120.30			− 983.9			.001048
			− 80.90	−485.40		−1,226.6	−.004750	
54	− 23	− 41.50			−1,469.3			−.003702
			44.45	266.70		−1,336.0	−.005173	
60	30	130.40			−1,202.6			−.008875
			333.70	2,002.20		− 201.5	−.000708	
66	38	537			799.6			−.009583
			769.00	4,614.0		3,106.6	.012020	
72	11	1,001			5,413.6			.002437
			500.50	1,501.5		6,164.5	.011930	
75	0				6,915.1			.014367

Col. 1 $M_A = M_o - M_i - R_1$ = residual gross bending moment.

TABLE IX.

DEFLECTIONS η_A.

Col.	1	2	3	4	5	6	7	8	9
r	$(M_A/I)\sin\phi$	Mean $(M_A/I)\sin\phi$	$(M_A/I)\sin\phi\, dr$	Σ_o^r	Mean Σ	$(d^2\eta_A/dr)\, dr$	η_A	$1000\times\eta/r$	$1000\times d/dr(\eta_A/r)\, dr$
15	26.6			0			0	0	
		31.85	95.6		47.80	.000093			.0052
18	37.1			95.6			.000093	.0052	
		33.35	200.1		195.65	.000756			.0302
24	29.6			295.7			.000845	.0354	
		12.10	72.6		332.00	.001286			.0358
30	− 5.4			368.3			.002135	.0712	
		−23.45	−140.7		297.95	.001154			.0202
36	−41.5			277.6			.003289	.0914	
		−35.25	−211.5		121.85	.000472			−.0018
42	−29.0			16.1			.003761	.0896	
		−31.45	−188.7		− 78.25	−.000303			−.0156
48	−33.9			−172.6			.003458	.0720	
		−21.75	−130.5		−237.85	−.000921			−.0250
54	− 9.6			−303.1			.002537	.0470	
		7.50	45.0		−280.60	−.001086			−.0228
60	24.6			−258.1			.001451	.0242	
		53.55	321.3		− 97.45	−.000377			−.0135
66	82.5			63.2			.001074	.0107	
		103.20	619.2		372.80	.001441			.0242
72	123.9			682.4			.002515	.0349	
		61.95	185.9		775.35	.001501			.0186
75	0			868.3			.004016	.0535	

TABLE X.

Relief and Net Bending Moments.

Col. r	1 Mean C	2 $C\,(d/dr)\,\zeta_A\,dr$	3 Σ^r_{tip}	4 $\cos\phi\Sigma$	5 $C\,(d/dr)\,(\eta_A/r)\,dr$	6 Σ^r_{tip}	7 $r\sin\phi\Sigma$	8 $-R_A$	9 M_A-R_A	10 M_{A1}	11 M^{11}
15	35,066	3.84	10.49	7.8	.182	1.900	19.1	26.9	1,305.9	1,252	10,119
18	30,420	29.40	6.65	5.2	.918	1.718	19.5	24.7	995.7	947	9,296
24	35,624	43.55	−22.75	−19.0	.917	.800	10.5	− 8.5	343.5	361	7,460
30	21,117	27.17	−66.30	−58.5	.429	−.117	− 1.6	−60.1	− 112.1	− 24	5,916
36	16,526	− 6.39	−93.47	−85.9	−.030	−.546	− 7.7	−93.6	− 411.6	− 246	4,479
42	12,117	−31.78	−87.08	−82.3	−.189	−.516	− 7.1	−89.4	− 256.4	− 109	3,836
48	8,150	−38.70	−55.30	−53.2	−.204	−.327	− 4.3	−57.5	− 192.5	− 95	2,725
54	4,845	−25.16	−16.60	−16.2	−.111	−.123	− 1.5	−17.7	− 40.7	− 13	1,881
60	2,350	− 1.67	8.46	8.3	−.032	−.012	− .1	8.4	38.4	23	1,051
66	754	9.07	10.13	10.0	.018	.020	.2	10.2	48.2	30	438
72	89	1.06	1.06	1.1	.002	.002	0	1.1	12.1	10	67
75			0			0	0	0	0	0	0

Col. 8 R_A = the relief due to the deflection from M_A = Col. 4 + Col. 7.
Col. 10 $M_{A1} = M_A{}^2/(M_A - R_A)$ = net residual B.M. (as per hypothesis).
Col. 11 $M^{11} = M_1 + M_{A1}$ = net B.M.

THIRD METHOD.

TABLE XI.

Col. r	1 M_1	2 $10^6\,(\delta r)^2/EI$	3 $M\,(\delta r)^2/EI$	4 $\sum_0^r$	5 C	6 δR	7 δM_0	8 δM_1	9 R_1	10 M_1+R_1
15	7,861	.1803	.001417						9,077.2	16,938.2
				.001417	35,066	49.7	− 410	− 360.3		
18	7,500.7	1.412	.01059						9,027.5	
				.012007	30,420	365.4	−1,540	−1,174.6		
24	6,326.1	3.567	.02256						8,662.1	
				.03457	25,624	886.0	−1,960	−1,074.0		
30	5,252.1	5.128	.02694						7,776.1	
				.06151	21,117	1,299.0	−2,521	−1,222		
36	4,030.1	7.692	.03100						6,471.1	
				.09251	16,526	1,529	−2,109	− 580		
42	3,450.1	12.35	.04263						4,948.1	
				.13514	12,117	1,638	−2,801	−1,163		
48	2,287.1	21.50	.04920						3,310.1	
				.18434	8,150	1,503	−2,469	− 966		
54	1,321.1	43.0	.05685						1,807.1	
				.24119	4,845	1,169	−2,196	−1,027		
60	294.1	102.75	.03023						638.1	
				.27142	2,350	630.2	−1,533	− 833.8		
66	− 599.7	331.8	−.1990						− 1.1	
				.07242	754	54.6	− 767	− 712.4		
72	−1,312.1	532.5	−.6984						55.7	
				−.62598	89	−55.7	− 94	− 149.7		
75	−1,461.8								0	−1,461.8

Col. $9 = \Sigma^r_{tip}$ of Col. 6.

Cols. 9 and 10 are only inserted for demonstrational purposes.

TABLE XII.

Col. r	1 M_{A1}	2 $10^6(\delta r)^2/EI$	3 $M_{A1}(\delta r)^2/EI$	4 Σ_0^r	5 C	6 δR_{A1}	7 R_{AI}	8 $M_{A1}+R_{A1}$	9 KM_{A1}	10 M_1+KM_{A1}
15	1.000	.1803	.00018				7.363.4	8,363.4	174.8	8,035.8
				.00018	35,066	6.3				
18	1,006.3	1.412	.001422				7,357.1		176	7,676 7
				.001602	30,420	48.8				
24	1,055.1	3.567	.003764				7,308.3		184.5	6,510.6
				.005366	25,624	137.5				
30	1,192.6	5.128	.006114				7,170.8		208.5	5,460.6
				.01148	21,117	242.5				
36	1,435.1	7.692	.01104				6,928.3		251	4,281.1
				.02252	16,526	372.1				
42	1,807.2	12 35	.02234				6,556.2		316	3,766.1
				.04486	12,117	543.4				
48	2,350.6	21.50	.05053				6,012.8		411	2,698.1
				.09539	8,150	777.3				
54	3,127 9	43.0	.1345				5,235.5		547	1,868.1
				.2299	4,845	1,114				
60	4,241.9	102.75	.4357				4,121.5		741.5	1,035.6
				.6656	2,356	1,568				
66	5,809.9	331.8	1.9275				2,553.5		1,015.5	415 8
				2.5931	754	1,955				
72	7,764.9	532.5	4.133				598.5		1,357.2	45.1
				6.7261	89	598.5				
75	8,363 4						0	8,363.4	1,461.8	0

$$K = \frac{1461.8}{8363.4} = .1748 = \frac{M_0 - M_1 - R_1}{M_{A1} + R_{A1}}$$

Col. 10 is the total net bending moment.

Cols. 7 and 8 are for demonstrational purposes only.

TABLE XIII.

CHECK FOR THIRD METHOD.

Col.	1	2	3	4	5	6	7	8	9	10	11	12
r	Net. B.M.	$10^6(\delta r)^2\,EI$	$M(\delta r)^2/EI$	Mean	Σ_0^r	Mean	C	δR	R	Gross B.M.	Error in Gross B.M.	% Error.
15	8,035.8	.1803	.001449		0				10,095.8	18,131.6	−268.4	−1.46
				.002080		.001040	35.066	36.5				
18	7,676.7	.3531	.002710		.002080				10,059.3			
18	7,676.7	1.412	.01084		.002080				10,059.3	17,736.0	−254	−1.41
				.017035		.010598	30.420	322.5				
24	6,510.6	3.507	.02323		.019115				9,736.8	16,247.4	−202.6	−1.23
				.025615		.031922	25.624	817.7				
30	5,460.6	5.128	.0280		.044730				8,919.1	14,379.7	−110.3	− .76
				.03046		.059960	21.117	1,267				
36	4,281.1	7.692	.03202		.075190				7,652.1	11,933.2	− 35.8	− .30
				.039715		.095048	16,526	1,570.5				
42	3,766.1	12.35	.04651		.114905				6,081.6	9,847.7	− 12.3	− .12
				.05227		.141040	12,117	1,709				
48	2,698.1	21.50	.05803		.167175				4,372.6	7,070.7	+ 11.7	+ .17
				.069165		.201757	8,150	1,645				
54	1,868.1	43.0	.08030		.236340				2,726.6	4,595.7	+ 5.7	+ .12
				.093350		.283015	4,845	1,371				
60	1,035.6	102.75	.1064		.329690				1,356.6	2,392.2	− 1.8	− .08
				.122200		.300790	2,356	920.8				
66	415.8	331.8	.1380		.451890				435.8	851.6	− 9.4	−1.09
				.117050		.510415	754	384.7				
72	45.1	2130	.0961		.568940				51.1	96.2	+ 2.2	+2.34
									51.1			
72	45.1	532.5	.0240		.568940							
				.0120		.574940	89	51.1				
75	0		0		.580940				0	0	0	0

Col. 2. All the terms of δr are inserted at this stage for convenience. As this is a check more significant figures have been given than are normally required.

REVIEWS.

Calculations from Drawings.

F. Holliday, B.Sc., A.F.R.Ae.S. Sir Isaac Pitman & Sons. 1944. 7s. 6d. net.

Mr. Holliday has had considerable experience of teaching aircraft apprentices and others and to quote from his preface to this interesting and unusual book: "To relate mathematics to reality is frequently more easily said than done. On the other hand, the teaching of mathematics is still too little illustrated and enlivened by really practical examples."

Mr. Holliday has collected his examples from the various works and technical departments of his firm, and there is no doubt about their practical value. They are excellent examples, indeed, as one would expect.

A knowledge only of trigonometrical ratios and of sine and cosine rules for solving triangles has been assumed.

This book requires careful reviewing. The idea of it is excellent and it is one which will prove very useful to fitters, toolmakers, junior draughtsmen and the like. There is a danger in it, however, in that the user may look through it to find the example which fits his problem and follow the calculations to some extent blindly. One would have preferred to see an opening chapter on the fundamental formulæ involved. The danger is emphasised in the author's preliminary note calling attention to the discrepancy between theory and practice in example 73. Theoretical experience is required for final judgment as well as practical experience.

Aeroplane Flight.

H. F. Browne. Longmans Green & Co., London. 1944. 7s. 6d. net.

Many books have now been written on the how and why of aeroplane flight, all aimed at explaining to those with little or no knowledge of aerodynamics what aerodynamics is, and how it affects the aeroplane.

It is a truism to say that most of these books are very elementary and general and would require a considerable amount of supplementing before the reader would be able to talk easily on the subject.

Mr. Browne has tackled the subject in ten chapters with the monologistic titles lift, stalling, drag, atmosphere, thrust, performance, control, stability, units and models. He works up gently from the atmospheric pressure on an ordinary matchbox to the causes for an aeroplane going into a spin, and does his work very well. The book is excellently illustrated by a large number of simple diagrams which amplify and complement the text.

There are a number of exercises at the end of each chapter. For the beginner this book is an excellent take off to a subject about which many experts still have their heads so much in the air that they find it difficult to make a good landing among those who wish to know how and why the aeroplane flew so well. Mr. H. F. Browne makes his three-point landing without much difficulty.

CORRESPONDENCE.

To the Editor of the JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY.

Sir,—While commending Mr. A. R. Weyl's letter in the July issue of the Journal, toning down to a more proper relative pitch the unquestionably important contributions of Professor Junkers to aircraft development, I would like to add a few words in connection with the question of the origin of the stressed skin design, cantilever wings, and the use of aluminium alloy.

The earliest, to my knowledge, attempt at skin stressed design can be found in the patent issued to Alphonse Pénaud and Paul Gauchet in 1876, in France. This patent, covering the construction of an aeroplane, which differed from our present aeroplanes only by the lack of provision for lateral control, specifies among other most remarkable features (for that period of time): " in case the surfaces of the wings should be of veneer or even of metal, we reserve making of the surfaces themselves the frame piece of the wings "—in other words, stressed skin construction of wings.

Mr. Weyl credits Levavasseur, the famous designer of the " Antoinette " monoplane, with producing a low-wing monoplane with cantilever wings in 1911. However, my recollection is that another Frenchman, M. Blanc, built a monoplane with full cantilever wings of wooden construction (with veneer cover), which was flown in 1912 or 1913, and that the Levavasseur monoplane with fabric covered wings and the trousered undercarriage was produced afterwards.

The exact dates could easily be found, for instance, in l'Aérophile, which recorded promptly such events but which, unfortunately, I do not have handy right now for verification, and I therefore venture this remark with due apology if my recollection is in error.

Regarding the use of Dural, it should be of particular interest that while this strong aluminium alloy was developed by Wilm, a German metallurgist, in 1903-1909, and acquired by Düren Metalwerke A.G. in Düren, Germany, who put it on the market in 1910, the first application to aircraft construction took place in England, the very same year, in the airship " Mayfly." The Zeppelin organisation started to use this new metal in 1916 and Junkers, in his monoplane " Ju 4," in 1917. I state this on the authority of a pamphlet giving the history of this development and published by the German manufacturers of this metal.

Yours very truly,

F. W. PAWLOWSKI, F.R.Ae.S.,

Guggenheim Professor of Aeronautical Engineering.

11th August, 1944.

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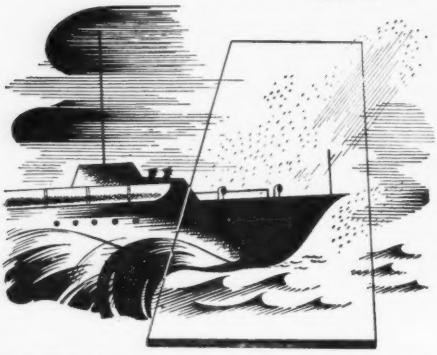

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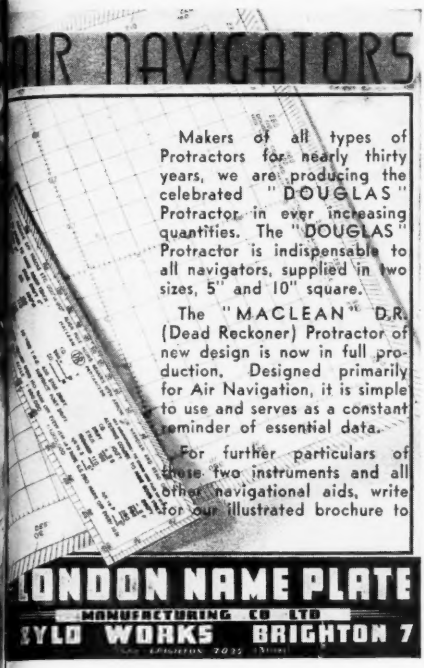
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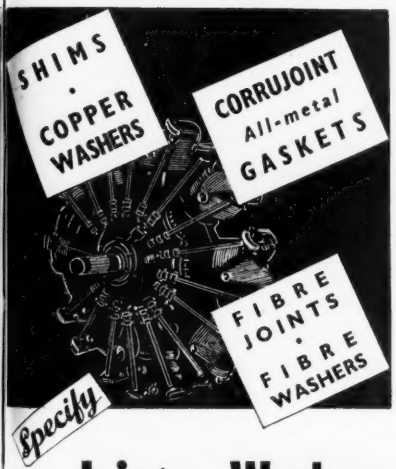

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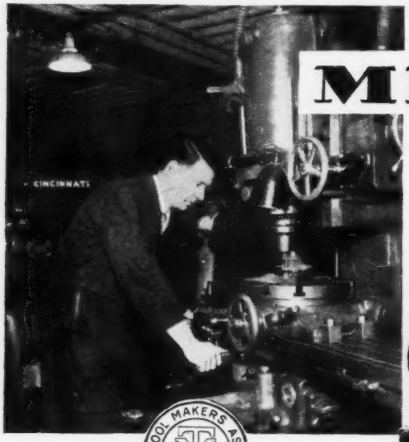

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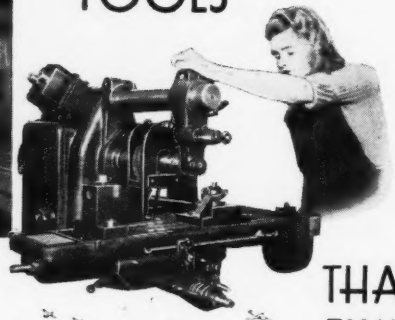

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